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THE MANUAL OF PHOTO-TECHNIQUE



THE MANUAL

OF PHOTO-TECHNIQUE

EXPOSURE

By W. F. Berg, D.Sc., Ph.D., F.R.P.S.

OPTICS

By Arthur Cox, B.Sc., M.A.

DEVELOPING

By C. I. Jacobson, Ph.D.

ILLUMINATION

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ENLARGING

By C. I. Jacobson, Ph.D.

RETOUCHING

By O. R. Croy, Ph.D.

Edited by A. KRASZNA-KRAUSZ

OPTICS

THE TECHNIQUE OF DEFINITION

By **ARTHUR COX, M.A., B.Sc., F.Inst.P.**

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I. Of all the components of photographic technique, optics has been linked longest with science proper. At a stage when the chemical aspects of photography still suffered from the comparatively crude means of trial-and-error practice, lenses were already made and tested on a basis reliably provided by the quantitative methods of physics.

This fact accounts for three effects. First, the development of photographic optics has always been conservative as compared with the frequent leaps of progress of photography in general. Secondly, books on photographic optics—provided they did not choose to be quite superficial—appeared to be more academic than books on any other chapter of photography. Lastly, the photographer, even if he were thoroughly interested in the different aspects of the techniques at his disposal, resigned himself to scraps of information as regards the performance of his lenses rather than be bothered by the intricacies of what must have appeared to him as higher mathematics.

Thus, the optical part of the equipment necessarily became a much less flexible instrument of photographic expression in the hands of the practical worker than negative material, processing or printing. The rise of the miniature camera, with its wide choice of interchangeable lenses and special finders, made the photographic public more optics-conscious than it was before, but it had little to rely on for reference apart from the somewhat dogmatic claims of manufacturers.

The man who designs a lens and the man who uses it in a camera, enlarger or projector, are interested in the same thing: is the lens the right one and the best one for the job in hand? But as long as they do not speak the same language the attitude of the "scientific" man is little understandable to his "practical" opposite number.

In this book a modest attempt has been made to get the photographer more interested and to help him to understand how his lens works and why, and what can be expected of it. Step by step, the reader without previous knowledge is led from somewhat loose definitions of terms met with in his daily work to explanations of the designer's difficulties and sobering qualifications of the manufacturer's claims. These vistas into the best use of lenses and their background are opened without using any but the bare minimum of formulae. Some, however, had to be included as one can no more talk about lenses without referring to the formulae than one can discuss developing without them. Their presence in this book may be found counter-balanced by an unusually large number of diagrammatic representations. "Pictures," by nature, can never tell the whole truth but what they tell of it is easier to perceive than the more exact meaning of an equation.

Particular care has been taken not to devote unduly large space to somewhat dry subjects. The details of coma, astigmatism, chromatic aberrations, etc., are matters for the optical specialist. Still, it is these faults or their absence that make or mar the performance of a lens and no discussion of the best type of lenses at present available can be introduced without an understanding of the nature of these possible faults.

II. The Tenth Edition of this work is being published ten years after the First. This fact offers an obvious confirmation of a success the degree of which is unusual for the type of subject. Author and publisher are naturally gratified by seeing thus proved that their efforts met such a real and vital need.

As the work went from edition to edition we have gladly made use of the

opportunities offered to keep all the information up to date and to clarify or elaborate it wherever possible. If in the course of this process the book grew richer in contents and more exact in making its points much of the credit is due to the many readers who took the trouble of asking intelligent questions. Even the best conception can be bettered if there is a chance for second thoughts ; even the best technical text can be improved if from time to time there is a chance for a new edition.

At the present stage the post-war development of the photographic industry in general and of optical design in particular having made a sufficiently wide impact, a thorough all-over revision of the work seemed to be called for. This revision was carried out by Mr. G. H. Cook of Messrs. Taylor, Taylor and Hobson Ltd., in Leicester, in the absence of the author Mr. Arthur Cox, chief optical designer to Messrs. Bell & Howell of Chicago.

These revisions have enabled us to carry out two measures interlinked with each other. It became possible to illustrate more fully the latest lens types, grouping them in such a way as to demonstrate their family likenesses and we could discard the elaborate listing of obsolete designs. There may have been a practical merit in tabulating older lenses, although discontinued by their manufacturers, as long as the photographer was forced to fall back on almost antique optical equipment during the war and the immediate post-war years. As once more modern lenses showing appreciable advance on their predecessors are offered in such wealth of choice there would be little justification in blurring the practical photographer's view by makes whose name may have by now acquired a somewhat legendary sound while their performance remains below the standards of to-day.

III. The reception of the tenth edition has fully justified the new approach to lens design. In the eleventh edition we have therefore merely had to bring the information up to date within the modified framework of the book.

Naturally, such a collection of data has only been possible with the co-operation of the manufacturers of optical equipment. Many of them have gone to considerable lengths to keep us posted on current developments and supplied with the latest information. We therefore take this opportunity to express our gratitude to the many firms in Britain, France, Germany, Holland, Italy, Japan, Switzerland and the United States of America who have so kindly assisted in the compilation of the material.

A. KRASZNA-KRAUSZ.

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THE FOLLOWING ABBREVIATIONS are used in the Tables XXII—XXXI to denote certain manufacturers' names :

| | | | |
|-----------|-----|-----|--------------------------|
| B. & L. | ... | ... | Bausch & Lomb. |
| Rodenst. | ... | ... | Rodenstock. |
| T.T. & H. | ... | ... | Taylor, Taylor & Hobson. |
| Voigtland | ... | ... | Voigtlander. |

LIGHT AND LENSES

Light

The greater part of our knowledge of the world about us is gained through the use of our eyes. The link between our eyes and the objects we see is *light*. This defines what we mean by light without, at the moment, saying anything about its nature. It is merely defined as the link between the viewing eye and the object that is viewed.

Light is to-day recognised as being something sent out by the object being looked at, that travels to the eye at the enormous speed of 186,000 miles per second, and that can stimulate the eye.

The first thing to notice is that it travels in straight lines. Except to a very minute extent light does not curl round the edges of obstacles that it cannot penetrate. Through some objects, those that are *transparent*, light can travel without any appreciable change. Others, those that are *opaque*, block it off completely. If a sheet of opaque material is held between the eye and a luminous point, *i.e.* one which is sending out light, then none of the light sent out reaches the eye.

Light Rays

This leads to the idea that every luminous point, whether it is sending out light because it is glowing like the filament of a lamp, or because it is illuminated by daylight or artificial light, sends out light in all directions. Each element of the light sent out travels away in a straight line, along the so-called *light ray*. *Rays of light* strictly speaking are the straight lines along which fractions of the light emitted are travelling. This is shown on p. 13. Not only does light stimulate the eye when it reaches it, but if it falls on a suitable surface, such as that of white paper, it illuminates this latter, and this in turn can send light rays to the

eye. (With pedantic accuracy this last statement should read : . . . *can send light to the eye along light rays*, but the phrasing used expresses the same thing in a more compact and standard form.)

Images

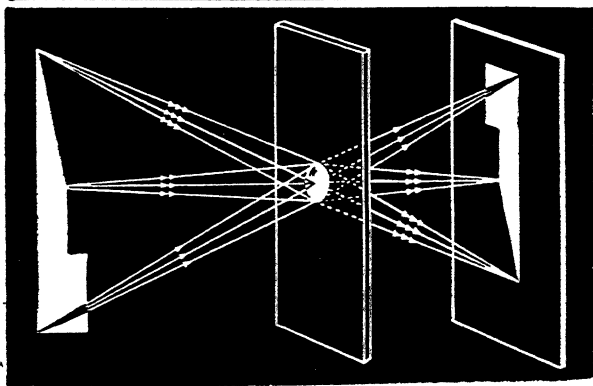
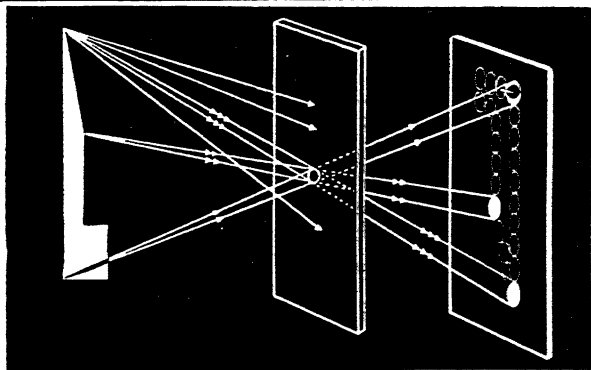
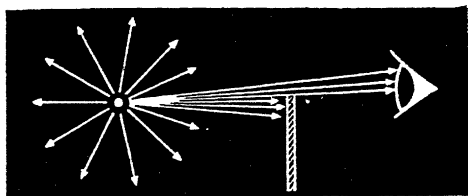
Now suppose that we have a flat surface, such as that of white card, and in front of it an opaque screen pierced with a fine pin-hole as shown on p. 13. If this arrangement is pointed towards a scene containing light and dark objects what happens is as follows : Every bright point in the scene sends out light rays. Some of these get through the pin-hole and give a small patch of light on the white card. This happens for each bright point. No rays are sent out by points in the scene that are completely dark. The result of this, as shown on p. 13 is that to every bright point in the scene there corresponds a small patch of light on the white card, and so on the card there is a rather diffuse replica of the original scene. This *is* the *image* of the scene.

Lenses and Foci

The rays of light from any bright point are spreading out until they come to the pin-hole, and continue to spread out after they pass it as already shown on p. 13. Better results are obtained if, by an arrangement of polished pieces of glass, the light rays are bent when they reach the aperture in the opaque screen, so that instead of continuing to spread out they now converge and meet again in a point as shown on p. 13. A replica is now obtained in which to every bright point in the original scene there may correspond a bright point on the white card, and as a result a much crisper and sharper image is obtained. The arrangement of glasses that bends the light rays in such a way is a *lens*.

The point to which the previously diverging light rays are brought by a lens is a *focus* or *image point*.

The simplest types of lens are shown on p. 15. They are



Top : A luminous point sends out light rays in all directions in straight lines. Only unobstructed rays reach the eye (p. 11).

Centre : Rays that get through a pinhole form a diffuse image (p. 12).

Bottom : By using a lens to bend the rays a sharp image is formed (p. 12).

LIGHT RAYS AND IMAGES

made from pieces of glass with polished surfaces, each surface being part of a sphere. The essential thing is that the centres of all these spheres lie on a straight line, as is especially clear in the figure, which shows a lens consisting of two glasses cemented together with Canada Balsam or one of the new synthetic cements. This straight line, about which the lens is symmetrical, is the *axis of the lens*.

Any particular lens can produce only a certain amount of bending of the diverging light rays that come to it. The more the rays are diverging when they come to the lens the less they are converging after they pass through it, and as a result the greater the distance away is the focus. This is shown on p. 15.

The greater the power of the lens to bend the rays of light that come to it, the closer in to it is the focus, all other things being equal.

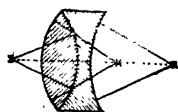
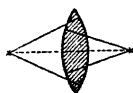
Focal Length

The extent to which lenses can bend the rays reaching them can be measured and compared in this way. Take a very distant luminous point such as one located on the surface of the sun. To all intents and purposes the light rays from this that reach any lens are parallel. Direct the lens so that its axis points towards the luminous point as shown on p. 15. The parallel rays are bent by the lens so that they meet again in a focus, called in this special case the *focal point* of the lens. The greater the bending power of the lens the closer to it is the focal point.

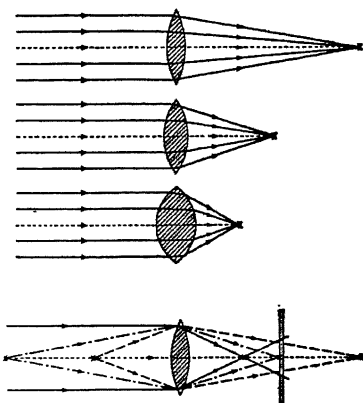
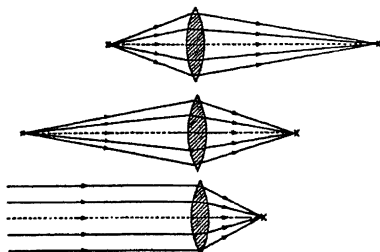
The distance of the focal point from the lens is the *focal length* of the lens. The important feature of a lens is its power to bend light and this is measured by its focal length. The shorter the focal length the greater the bending power of the lens. (It is possible also to have a lens which causes light rays to diverge rather than converge, this is dealt with in later chapters.)

In the definition just given there is a certain amount of ambiguity in the part of the lens from which the position

Right: The simplest form of lens consists of a piece of glass with polished spherical surfaces. Its axis is the line joining the centres of these.



In a properly adjusted lens of more complex form, such as the cemented doublet shown, the centres of all the spherical surfaces lie on a straight line, the axis of the lens (p. 14).



Left : As the point sending light moves away from the lens the rays of light that reach the lens become less divergent (second diagram), until when the point is at infinity the rays are parallel (third diagram). At the same time the emerging rays become more convergent and the image lies nearer in to the lens. When the incident rays are parallel the image is the focal point (p. 14).

Above : Three diagrams indicate parallel rays of light coming from infinity and converging to the focal points of the lenses in question. We see that the power of the lens to bend light depends on its shape. The deeper the curves on the glass the stronger the lens. As the power of a lens increases the distance of the focal point, or focal length, decreases (p. 14).

Bottom : The Image of only one point at a time can be focused on a plate or film. The light from other points is focused in front of, or behind the film, and on it forms comparatively un-sharp discs of varying sizes ; this gives rise to *depth of focus* (p. 16).

THE ACTION OF LENSES

of the focal point is to be measured. The last glass-to-air surface is not always the proper base from which to measure it. A more exact definition is given in the following chapter where the properties of lenses are considered in greater detail.

Images and Focusing

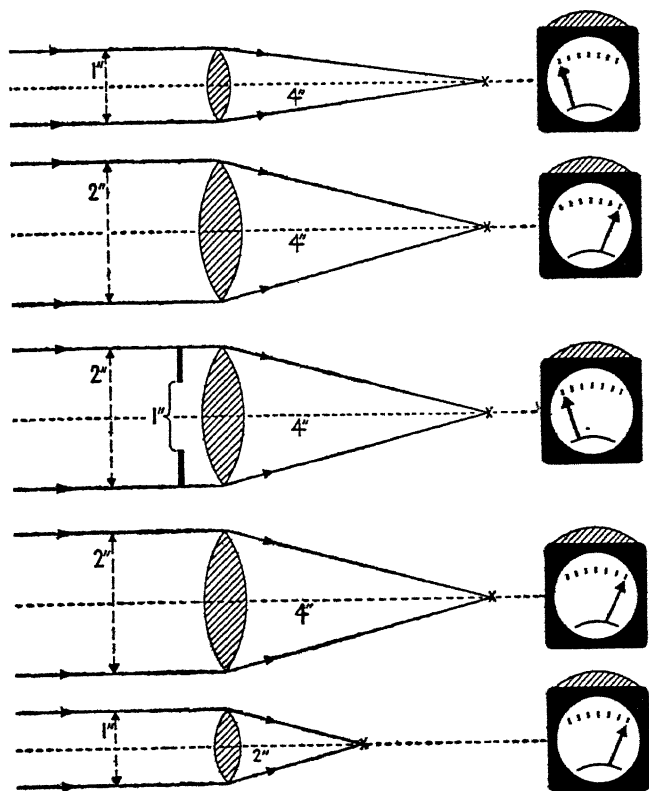
Now consider any point in front of the lens and sending rays of light to it. The divergence of these rays is fixed once the distance of the point from the lens is settled. As a result the convergence of the rays emerging from the lens is determined uniquely, and so is the position of the focus corresponding to that particular point.

One result of this is that foci or image points corresponding to all the multitude of luminous points in front of a lens do not lie in the same plane. Any particular element in the picture has its sharpest and crispest image or replica at the point where the rays from it are brought to their foci. If now it is required to bring a sensitive plate or film to the position where it will receive the sharpest image of some elements of the scene, an adjustment of the lens and plate position has to be made so that the image points corresponding to these elements will lie on the plate. Such an adjustment is spoken of as *focusing the lens*, and the lens is *focused upon* those particular elements.

When the lens is focused on a certain group of points or objects, so that the light rays are bent to meet again on the sensitive plate or film, then the rays from all other points meet either in front of or behind this plane and form light patches of small but finite size upon it. These other objects or points are *out of focus* (p. 15).

Depth of Focus

When an object is focused on a ground-glass surface or screen, or upon a sensitive plate then its image is at its sharpest and crispest. When it is distinctly out of focus



The brightness of an image depends on the f /number of the lens, i.e., the diameter of the beam going through divided into the focal length. The examples show (top) an f 4, (second diagram) an f 2, and (third diagram) an f 2 stopped to f 4 by a metal diaphragm. The smaller the f /number the greater the image brightness indicated by the response of an exposure meter (right). If the beam diameter and focal length are both halved (fourth and bottom diagrams) the f /number and image brightness remain unchanged. These examples again show f 2 lenses (p. 18).

IMAGE BRIGHTNESS

the image is very diffuse and as a rule is of no particular interest. There is, however, an intermediate region where, although the image is not perfectly sharp, it is of an acceptable standard of sharpness. Because of the existence of this region of acceptable image quality the lens is said to have a *depth of focus*. The exact extent of the depth of focus or region of acceptable quality depends on a number of factors and is discussed in detail in later chapters.

f/numbers

In many instances it is important to have a comparison of the amount of light that goes through a lens. For astronomical work the feature that determines the brightness of the image produced is the diameter of the lens. But for normal everyday photography the only useful measure of the light going through the lens, of the brightness of the image it produces, is the ratio of the focal length of the lens to its diameter, its *f/number*. Thus if a lens has a focal length of 4", and a diameter of 1" it is an *f 4* lens. The greater the *f/number* the less useful light goes through the lens and the less bright the image formed. Doubling the *f/number* reduces the image brightness to one-quarter (p.17).

The *f/number* in any actual lens is changed in accordance with the requirements of the occasion by changing the diameter of a hole in an opaque *diaphragm* or *stop*. As a rule nowadays this is effected by the movement of a group of curved metal leaves sliding over one another in an *iris diaphragm*.

Aberrations

So far the assumption has been made that a lens can be constructed so that it will bring a group of diverging rays to a focus, in a sharp image point. Such a lens would have many of the attributes of a perfect lens. When it comes to the question of shaping glass, either practically in the shops, or in the mind of the designer to give this

result, It has to be admitted that the problem is Insoluble. It is known on theoretical grounds, from the nature of light, that the problem is insoluble. But that does not mean that a good approximation to a solution cannot be made. What is obtained in place of a sharp image point is a small illuminated light patch.

The defects in the performance of a lens which result in its bringing rays of light to a small patch of light, instead of to a sharp point, are the *aberrations*.

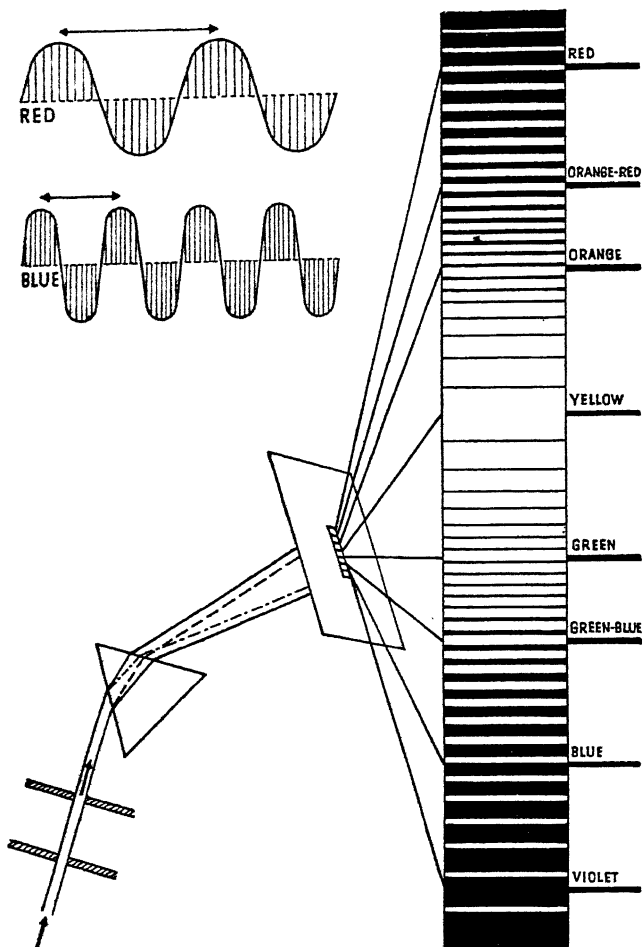
Spectrum

Of the aberrations an interesting group depend on the fact that the extent to which any ray of light is bent by glass depends on the colour of the light. This is shown especially on p. 20. By the arrangement of slits shown a narrow pencil or beam of light rays is produced, say a narrow beam of sunlight. This beam traverses a prism, being bent or *refracted* at each glass to air surface. Owing to the varying extents to which the light making up the original beam is bent, there emerges from the prism not a single beam of light, but a number of coloured beams. If these fall on white card they produce a coloured patch of light, a *spectrum* that shades off from red, through orange, yellow, green, and blue to violet. The arrangement of colours in a spectrum is just that seen in a rainbow.

These are the colours of light that can be seen by the eye. They also affect a photographic plate or film. But in addition there is something sent out by most glowing bodies or illuminated objects, that travels in straight lines like light, that behaves in practically the same way as light except for the fact that although it can influence a photographic plate it does not stimulate any response by the eye. It is *invisible light*, or *radiation*.

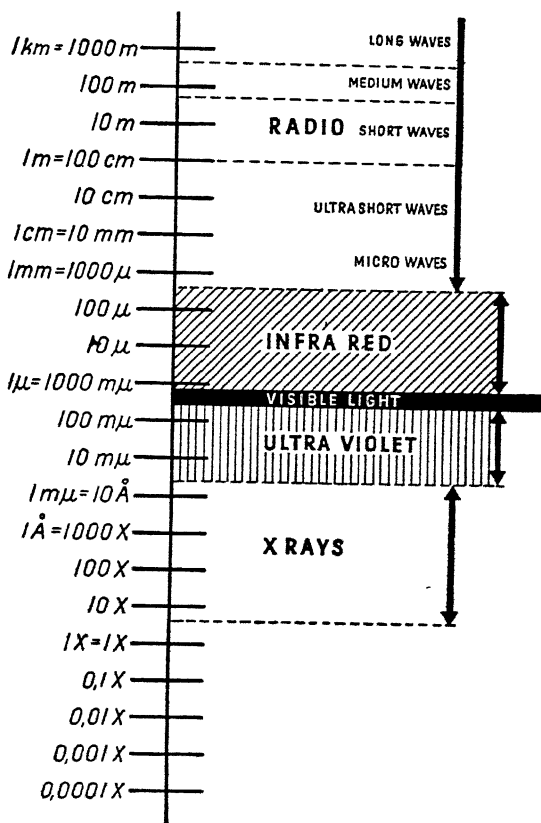
Two kinds of invisible radiation are of particular interest, *infra red* and *ultra-violet* radiation.

To understand what these are means taking more note of the nature of light.



There is a regularly repeated pattern of electric force along a light ray. The size of the unit of the pattern is the wavelength. The wavelength of red light (top left) is about double that of blue light (p. 22). A beam of white light is split by a prism into its component colours, and produces a spectrum on a screen ; the colours produced range from red to violet (p. 19).

THE SPECTRUM



There is an extended range of radiation possessing a repeated pattern of electric force, of which light (p. 20) forms only a very limited part. The property of the radiation depends on the wavelength, and the means of detecting it also depend on its wavelength. The wavelength of light is so small that a special unit is used to measure it, the *Angstrom Unit* (Å) of which there are ten million in a millimetre. The extreme shortness of X-rays leads to the use of the *X unit* of which there are ten thousand million in a millimetre. Other units in between are the micron (μ) and the milli-micron (mμ).

LIGHT AND RADIATION

Wavelength of Light

Suppose at some instant that we could freeze things, prevent further change, and see what are the conditions along a ray traversed say by blue light. At any point on the ray there is an electric force. This force varies from point to point along the ray in a regularly repeated pattern as shown on p. 20. The distance between corresponding points in the repeated pattern is the *wavelength* of the light.

Light is of essentially the same nature as the disturbance sent out by a radio transmitter. In radio the wavelength of the repeated pattern of electric force is about 2,000 metres in the long wavebands, down to five or seven metres in the very short wave bands, and can only be recorded by instruments especially designed. In the micro-wave bands the wavelength is reduced to a few centimetres and again special apparatus is needed.

As the wavelength is still further decreased, until it is only a few hundred-thousandths of an inch, the conditions under which the radiation is sent out and perceived change radically. It is now capable of affecting a photographic plate and of producing a feeling of warmth on the skin. It is *infra-red light* or *infra-red radiation*.

With a reduced wavelength it is capable of stimulating the human eye and producing a red colour sensation. It is in fact *red light*. At this stage the wavelength is about .00003 inch.

Further reductions of the wavelength take the colour of the light through the entire range of the spectrum, until at a wavelength of .000015 inch the light is violet. Any further decrease takes it into the ultra-violet, and after that into the region of X-rays (p. 21).

As far as photographic optics is concerned, the only region of interest, out of the totality of radiation, comprises the visible spectrum and the near infra-red and ultra-violet bordering on it. It is in this region that photographic lenses and equipment are designed to work.

THE IDEAL LENS

Perfect Definition

No lens yet made is perfect.

A perfect lens would reproduce every point of light as an exact point on the sensitive material or focusing screen, and reproduce every straight line as a dead straight line.

Any actual lens falls away from this ideal. A point of light is reproduced as a patch of light of finite size. A straight line is reproduced as a narrow band of light, usually curved instead of being straight. But there are times when there is really no difference between a point and an illuminated area of .002" diameter, when the width of the reproduced band is negligible by ordinary standards, and when its curvature is barely noticeable. By ordinary standards the lens is behaving perfectly, even though it is far from perfect by really critical standards.

The best way of dealing with any lens is to assume first of all, that it is perfect, that it reproduces points as points, and lines as lines.

From this point of view a broad outline of the lens performance can be given.

The second stage is to set up really critical standards and to see how imperfect the lens actually is by these.

The first step is taken in this chapter. Any lens considered is taken to be near enough perfect, and an account is given of the way in which it will therefore perform: the finer details of its virtues and vices are dealt with in later chapters.

It will then be taken for granted, throughout this chapter, that a lens reproduces a point of light in front of it as an exact point on a plate or focusing screen, and that it reproduces a straight line on a plate or screen as a straight line.

Bearing this in mind, the first thing is to be able to describe a lens in a useful way.

Focal Points

It is obvious how to do this.

Every lens catalogue refers to lenses as 6" f 4.5, as 2" f 2, and so on, and this description seems adequate for most purposes. The 6" and 2" refer of course to the focal length of the lens. But it is not so obvious as to what exactly is the focal length of a lens, what it is the length of, and between what points it is measured.

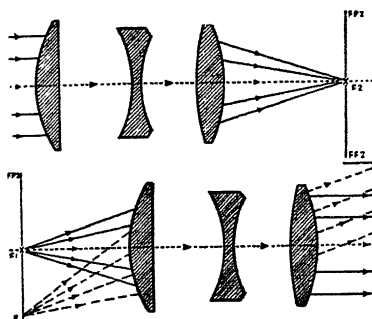
It is so absolutely necessary to have a clear idea of what is meant by focal length, and of the points between which it is measured, that it is worth while going into the matter fully, and describing such things as focal points and nodal points in detail.

When the object in front of the lens is a point of light on the lens axis at an infinite distance, then all the light from it, that goes through the lens, is brought to a focus at the "rear focal point." This is marked as $F 2$ on p. 25. The light that enters the lens in this case is composed of parallel rays : because of the infinite distance that they have to travel from the object to the lens they need diverge from one another only by an infinitesimal amount in order to fill the lens aperture.

The plane at right angles to the lens axis through the rear focal point $F 2$ is the "rear focal plane." Every object at infinity is reproduced sharply in the rear focal plane. The rear focal plane is also shown on p. 25.

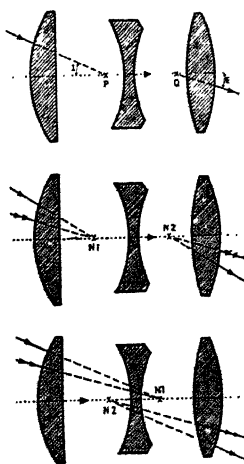
There is another focal point of equal importance, the "forward focal point" marked as $F 1$ on p. 25, and a plane through this at right angles to the lens axis, the "forward focal plane." *When the object in front of the lens is a point of light at the forward focal point, the rays of light emerging from the lens are all parallel to the lens axis, as shown on p. 25.* And when the object is a point of light somewhere in the forward focal plane the rays of light emerging from the lens are all parallel to one another, making an angle with the lens axis, as also shown on p. 25.

These constitute the two focal points of the lens. The other two points of importance are the two nodal points.



Top : Parallel rays of light are brought to a focus by an ideal lens in the rear focal point F_2 . FP_2 is the rear focal plane.

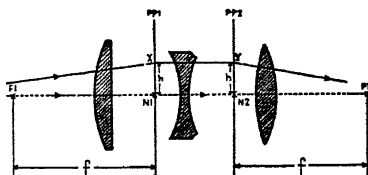
Lower : Rays from the forward focal point F_1 emerge as a bundle of rays parallel to the lens axis. Rays from any other point P in the forward focal plane emerge as a bundle all equally inclined to the lens axis (24).



Top : The angle of incidence I of a ray aiming at P is not as a rule equal to the emergent angle E that the ray makes with the lens axis (p. 26).

Centre : When the ray aims at the forward nodal point N_1 the angles of incidence and emergence are equal for all rays (p. 26) and any emerging ray is parallel to the ingoing ray from which it is derived.

Below : The nodal points N_1 and N_2 may be crossed so that N_2 is in front of N_1 (p. 26).



Above left : The forward and rear principal planes PP_1 and PP_2 are drawn through the nodal points N_1 and N_2 . Any ray cuts each at the same distance from the axis. The focal length f is the distance between each nodal point and focal point (p. 27).

FOCAL AND NODAL POINTS

Nodal Points

Suppose that a ray of light is going into the lens, aiming at a point P on the lens axis, as shown on p. 25. After bending at the lens surfaces it finally emerges from the lens, aiming away from the point Q . In general it makes a different angle with the lens axis before it enters the lens, to the angle it makes with the axis after leaving the lens. For instance, the ray aiming at the point P may make an angle of ten degrees with the lens axis, and the emerging ray, aiming away from Q , may make an angle of perhaps eight or twelve degrees, say, with the axis. The actual ratio between the emerging and entering angles depends on the positions of P and Q relative to the lens.

The important case is that in which the angles are equal, no matter what the actual size is in degrees. In this case the entering ray aims at the "forward nodal point," marked $N1$ on p. 25, and the emerging ray aims away from the "rear nodal point," marked $N2$.

There is one possibility to notice. Although the nodal points are called forward and rear nodal points, it may happen that they are crossed over and the forward nodal point may be behind the rear nodal point. This is shown on p. 25.

The essence of calling them "forward" and "rear" is that a ray coming in from the front of the lens aims at the forward nodal point, and coming out of the lens aims away from the rear nodal point.

To complete this section, the next thing to do is to consider the planes at right angles to the lens axis through the nodal points. These are the "*principal planes*." The forward principal plane $PP1$ on p. 25 goes through the forward nodal point $N1$; the rear principal plane $PP2$ goes through the rear nodal point $N2$.

The principal planes have this important property: If a ray of light goes into the lens aiming at a point X in the forward principal plane, then it comes out of the lens aiming away from a point Y in the rear principal plane, and Y is the same height above the axis as the point X . This is shown on

p. 25. When the nodal points are crossed over, the principal planes are crossed over. This makes no difference to their properties as described above.

Focal Length

The forward and rear focal points are put in on p. 25 for the sake of completeness and because the relative positions of focal and nodal points are important.

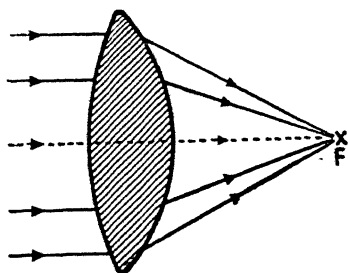
Detailed mathematical work shows that the distance from the forward nodal point N_1 to the forward focal point F_1 , is exactly the same as the distance from the rear nodal point N_2 to the rear focal point F_2 . This distance, marked as " f " on p. 25 is the "equivalent focus" or "equivalent focal length" of the lens. When the focal length of a lens is given without any further qualification, it can be taken for granted that it is the equivalent focal length that is meant, and not the back focal length that is described below.

A normal photographic lens is a converging lens. Rays of light from a distant point come out of the lens so that they all converge to a point as shown on p. 28. It is possible, though, to have a diverging lens. In this case, rays of light from a distant point come out of the lens as if they diverged from a point in front of the rear nodal point, as shown on p. 28.

When the lens is converging the focal length is said to be *positive*. When it is diverging the focal length is *negative*, and the lens is often spoken of as being a negative lens. In the same way a converging lens is often called a positive lens.

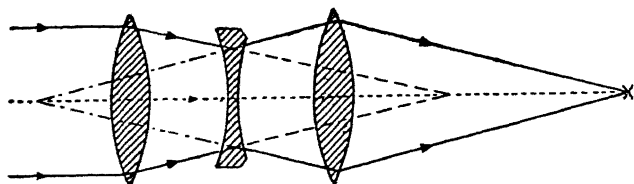
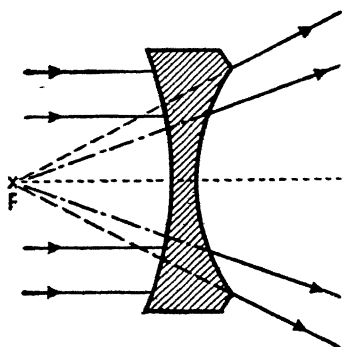
Negative lenses only enter into photography in very special circumstances, such as when they are used as supplementary lenses (see p. 190), and throughout this book, unless a special mention is made, it can be taken for granted that any lens referred to is a positive or converging lens.

Once the positions of the focal points and nodal points are known (or what comes to the same thing, when the focal length is known as well as the positions of the nodal points)



Left : Parallel rays of light are bent by a converging lens so that they converge to a focus at F (p. 27).

Right : A diverging or negative lens bends the rays so that they diverge from a focus F . In this case and in that shown above the nodal points are inside the glass. Their exact positions depend on a number of factors, such as the shape of the lens, and the individual type of glass used. (p. 27).



Above : In all but the simplest photographic lenses converging and diverging lenses are combined so that their resultant effect is to cause rays of light to converge. Thus they form a complex converging lens (p. 27).

CONVERGING AND DIVERGING LENSES

relative to such features of the lens mount as shoulders and flanges, quite a lot can be worked out. Everything needed in arranging the lens for any type of work can be calculated and worked out on paper, from focusing scale markings to enlarger settings. Some of these topics will be dealt with later in this chapter.

Measuring the Focal Length

As far as focal length is concerned the maker's nominal value engraved on the lens can usually be relied upon to within 1 per cent or less. And for that matter any information about the positions of nodal and focal points can be obtained from the makers. But it is sometimes useful to be independent of the makers as far as obtaining this information is concerned. What follows is, therefore, a short account of the principles involved in determining focal lengths and so on. Details of improvising apparatus are best left completely to individual cases, and only the general ideas common to all are given.

The first thing to do is to find the position of the rear focal point or focal plane.

By the definition of this, it is the plane in which the image of an infinitely distant object is formed. For any lens of the size used in cameras the difference between an object at a thousand yards and one at infinity is negligible as far as finding the rear focal plane is concerned. For a lens of 6" focal length the error introduced is only .001". The only thing to do then is to focus some object, at a distance of about a thousand yards or over, on a focusing screen, and measure the distance of the screen from the lens. This gives the position of the rear focal plane and rear focal point. The distance of the screen from the middle of the last glass surface is the "back focal length" or "back focus" of the lens.

To get the position of the forward focal point the simplest thing to do is to turn the lens round, so that the glass surface that usually faces the distant object now faces the

focusing screen. Then find the rear focal point of this turned-round lens. *This point is the forward focal point of the lens in its normal position, relative, of course, to the lens and not in absolute position.*

It will probably be found that, in focusing a lens turned round in this way, it will be necessary to stop it down to a small aperture to get a reasonable definition, and one that will stand examination with a 10x or 15x magnifier, such as is normally used to examine the image on a focusing screen. If the definition is at all soft, with the lens turned round in this way, it is the proper thing to stop down to improve the definition and then to find the best focus, rather than try to find the best focus with soft definition on the screen.

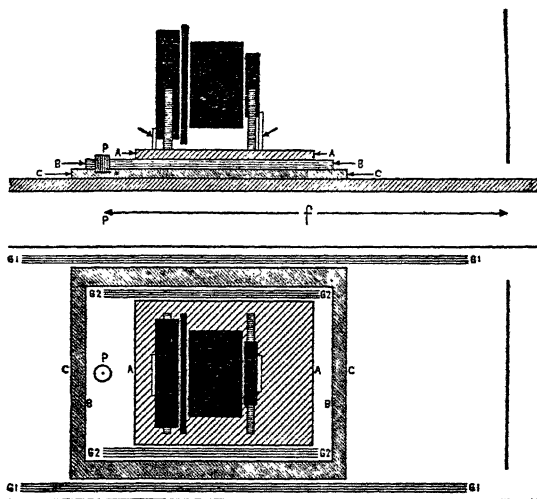
In dealing with both rear and forward focal planes another practical point must be borne in mind. In view of the fact that no lens is perfect, it may happen that the field is curved, and objects whose images lie away from the centre of the focusing screen may be in sharp focus with an image in the centre of the screen slightly out of focus. In this case the position of the focal point is found by getting the central image dead sharp. (See also the notes on focusing on p. 288.)

The third and last thing to do is to find the position of a nodal point.

Using a Nodal Slide

To do this some improvised form of "nodal slide" must be used as shown on p. 31. The lens can be mounted in V-grooves cut in quarter-inch wood uprights which are fastened to a baseboard A, and held in position by stops bearing against front and back of the lens mount. The depth of the grooves in relation to the part of the lens mount against which they bear has to be adjusted so that the lens axis is horizontal. This can be done within very close limits by placing a 90 degree set square against the front or back of the lens mount and against the baseboard.

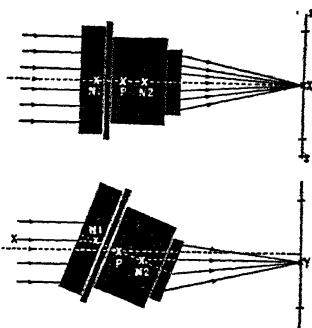
This lens carriage A is carried on a second B, as shown, and it can slide between ways on B in a direction parallel to



Top : The sliding and swinging platforms that constitute a nodal slide are shown in plan and elevation. When the final adjustment is made the distance of the pivot P from the focusing screen is the focal length f (p. 33). In the diagram the pivot is shown as being in front of the lens when the final adjustment is made. This situation only arises with a telephoto. With a normal lens the pivot is near the back of the lens when the setting is made as described in the text.

Right : When a lens pivots about any point other than the rear nodal point N2 there is a shift of the image on the screen. This is the basis of the nodal slide. The

reason is that all the rays emerging from the lens go through the image of the point at Infinity. Among these rays is one through the rear nodal point parallel to the incident set. Hence if there is any movement of the rear nodal point the image lies on a line shifted laterally from its first position and so there is a movement of the image. When the pivot coincides with the nodal point there is no movement of this latter and so no movement of the image (p. 32).



THE PRINCIPLE OF THE NODAL SLIDE

the lens axis. This direction again can be fixed by means of a set square placed against the front of the lens mount.

The second carriage *B* rests on yet a third *C*. The surfaces of *B* and *C* in contact are finished as smoothly as possible so that they can move over one another with the minimum of friction. The carriage *B* can swing about on a vertical axle carried by *C*. It is essential that the movement about this pivot should be perfectly smooth, and there must be no play between the axle and the hole in *B* into which it fits. There are various ways of arranging this : one is to cut the hole in *B* rather larger than is needed and form a close fitting bearing surface by pouring in Wood's metal or other low melting-point alloy.

The carriage *C* can slide backwards and forwards on the base of the whole apparatus in a direction parallel to the lens axis. This is effected by keeping it pressed up against a runner, as shown on p. 31, which has already been set parallel to the lens axis.

The final requirement is a focusing screen of ground glass which is set at right angles to the lens axis, or what is the same thing at right angles to the runner guiding the movement of the carriage *C*.

The carriage *B* is brought to its central position and the lens carriage *A* moved backwards or forwards until a distant object is in sharp focus at or near the centre of the focusing screen, i.e., where the lens axis cuts the screen as nearly as can be judged by eye. The carriage *C* is not touched at this stage. With an object at infinity or at a great distance all the rays of light from it that reach the lens are sensibly parallel.

The carriage *B* is then pivoted through two or three degrees. What usually happens is that the image on the focusing screen moves to one side or the other.

On page 31 is shown why this happens. The original position of the lens is shown with the nodal points at *N1* and *N2* and the pivot at *P*. The parallel rays of light are brought to a focus on the screen *S* in the rear focal plane. The lens position is shown next after it has been swung

through a few degrees (exaggerated in the diagram). One of the parallel rays entering the lens goes through the forward nodal point N_1 , as illustrated by the actual ray in question $X-N_1$. It emerges from the rear nodal point as the ray N_2-Y , parallel to $X-N_1$ as shown. Since all rays from a distant point come together in a point after passing through the lens, the image of the distant point must lie somewhere on the ray N_2-Y . That means, as is shown on p. 31, that with the lens swinging the image moves sideways. Actually it also moves out of focus slightly, but not enough to matter with a small swing of the lens.

The carriage C is then moved away from or towards the focusing screen, and the image refocused (with the carriage B in its central position) by moving the lens carriage A . *This adjustment is carried out until there is no sideways movement of the image or the screen when B is pivoted through a degree or two.* It is useful to have fine pencil lines ruled on the ground glass surface to detect most easily the absence of movement.

When this happens the nodal point N_2 coincides with the centre of the axle or pivot carried by the carriage C . There is then no movement of N_2 as the lens pivots and no consequent movement of the image.

All that is necessary then is to measure the distance of the centre of the pivot from the focusing screen. This gives the focal length, which has already been defined as the distance from the rear nodal point to the rear focal plane.

The forward nodal point is found by measuring off a distance, equal to the focal length from the forward focal point, which has already been located as described above.

The method of measuring focal lengths just described is only one out of a number of possible ways. The two alternative methods given below are in some ways easier to apply with improvised or readily available apparatus.

The first is adapted for occasions when outdoor photography is possible, and when a street map or Ordnance map is available. The procedure then is : Take a photograph (with the lens, the focal length of which is wanted, mounted in some suitable camera) of a scene in which some prominent parts can be picked out on an Ordnance map.

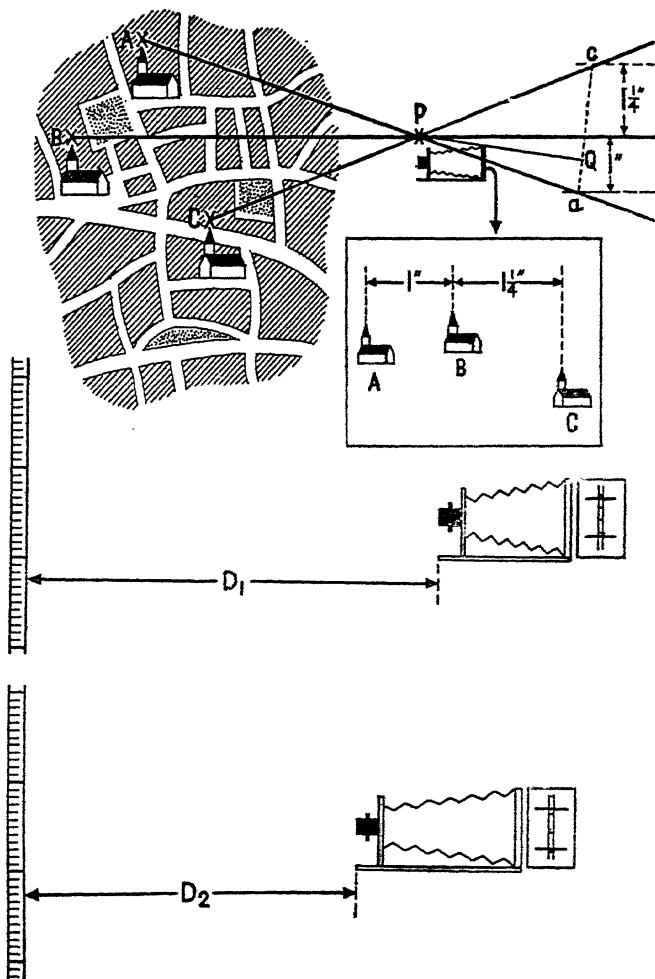
Church steeples are especially useful for this purpose. Note on the map the position of the camera and three other points, if possible more than a thousand yards away from the camera. In the diagram on p. 35 the camera position is marked by *P*, and the objects on which attention is to be concentrated when the exposure is made and the negative fixed, are taken to be three steeples at *A*, *B*, and *C*. Join *PA*, *PB*, and *PC* and continue the lines as shown in the diagram. In the negative measure the distances from one another of the images of the steeples. Suppose that these are 1 inch from *A* to *B*, and $1\frac{1}{2}$ inch from *B* to *C*, as also shown on p. 35. On the map draw one line parallel to *PB* 1 inch away from it, and on the opposite side of it to the point *A*, and another $1\frac{1}{2}$ inch away on the other side of *PB*. These cut the lines already drawn on the map in *a* and *c* respectively. Join *a* and *c* and measure their distance apart : suppose that it is 3 inches. Next draw a line *PQ* from *P* at right-angles to *ac*, and measure its length : suppose that it is 6 inches. Then the focal length of the lens is equal to 6 inches $\times 2\frac{1}{2} \div 3$, i.e., $4\frac{1}{2}$ inches ($2\frac{1}{2}$ inches is the separation of the images of *A* and *C* on the negative).

The other method is specially applicable to cases where outdoor photography is not possible. It is also useful when plates and films are scarce as it can be carried out quite efficiently with the use of a focusing screen in the camera instead of a plate. In outline it consists of photographing an object from two positions not very distant from the camera, or alternatively noticing the size of the images on a focusing screen under the same conditions, measuring the image sizes and at the same time the distances of the object from the camera. Proceed as follows :

Hang a tape-measure in front of the camera in which the lens under test is mounted, and make sure that the focusing screen in the camera is vertical and so parallel to the tape-measure. Move the camera either nearer to or farther from the measure until 20 inches of this latter form a sharply focused image that occupies exactly 2 inches on the focusing screen, i.e., the system is working at a reduction of 10 to 1. Then measure the distance of the tape-measure from some definite point on the camera or lens mount as shown in the diagram on p. 35. Next repeat the procedure so that a length of 40 inches of the measure now occupies a length of exactly 2 inches on the focusing screen, and the system is working at a reduction of 20 to 1. Again measure the distance of the tape-measure from the camera. Then the difference between the two distances from the camera is equal to 10 times the focal length of the lens. More generally the formula is : If the distance between the two camera positions is *D* and the difference between the two degrees of reduction is *M*, then the focal length of the lens is given by $D \div M$. The example given above will make it clear how this formula is to be used.

The Point of View of the Lens

The camera does not see any scene in exactly the same way that it is seen by any human observer. When one looks at a scene there is more to it than the mere formation of an image on the retina of the eye, there is in addition a series of psychological phenomena to be taken into account. For



The top diagram shows a method that is suitable for out-door work (p. 34). The lower diagrams illustrate a method that is particularly useful when one is restricted to indoor work (p. 34).

DETERMINING THE FOCAL LENGTH

Instance it is a photographic commonplace that if the camera is taken too near to a subject then the resulting print shows a very pronounced distortion of the relative proportions of the subject. Those parts near the lens are grossly enlarged. One never encounters this in real life unless it is specially looked for. If one looks at a scene from the same viewpoint as a lens that is giving a distorted image this distortion is not immediately evident to the eye. The mental processes that are called into play allow for the increase in size of the image formed in the eye.

Because of the more direct and less interpretive recording of a scene given by a lens, and the fact that it may differ in important respects from the way in which the same scene is apprehended and automatically interpreted by the combination of brain and eye, it is of importance to consider in detail the way in which a camera views a scene.

Every ray that goes into the lens aiming at the forward nodal point, comes out of the lens aiming away from the rear nodal point, and travelling in a direction parallel to its entering direction.

Suppose then that a fan of rays is drawn from the forward nodal point to all points in the objects to be photographed. To these rays there corresponds a fan of rays leaving the rear nodal point and going to the photographic plate, as shown on p. 38. This second fan of rays are arranged among themselves in exactly the same way as the first, and make exactly the same angles with one another that are made by the corresponding rays in the first fan. The whole set of rays from the rear nodal point is upside down relative to the set of rays drawn from the forward nodal point to the object points, but this is of minor importance. What is important is the fact that the angles between the rays are the same for both sets.

If a frame, the size of the plate or film being used, is placed in front of the forward nodal point at the same distance that the plate is behind the rear nodal point (not the focal distance except when the objects are at infinity), then the fan of rays from the forward nodal point traces out, in this

frame, exactly the same pattern that the rays from the rear nodal point trace out on the plate or film. The fact that one of these patterns is upside down is of no material importance.

The picture thrown on the film or plate is just that which an eye, placed at the forward nodal point, would see framed by a rectangle the size of the plate, held at a proper distance. That distance is equal to the distance of the sensitive plate from the rear nodal point.

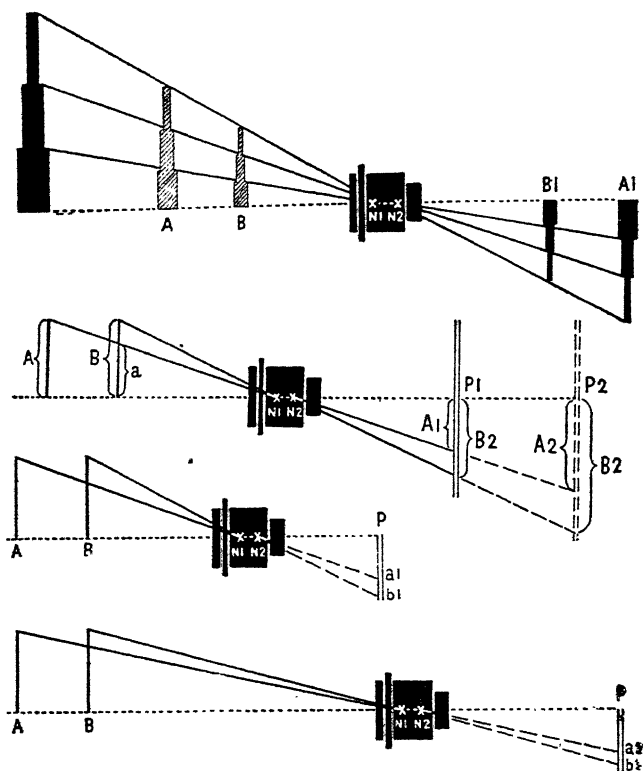
There is one qualification to make. The eye, viewing such a framed picture, can change its accommodation and focus every element of the picture separately in an almost unconscious fashion. This is out of the question with the camera lens. Elements of the picture included in the frame may be quite a long way out of focus and hardly recognisable. But as far as they are recognisable on the plate their positions and relative sizes are given by the considerations outlined above.

Image Size and Focal Length

With a given subject to be photographed the largest image is obtained on the plate when the frame in front of the nodal point (we can call it the perspective frame) is near to the subject or even beyond it, as shown on p. 38. When the frame is beyond the subject an enlarged image is obtained, and this may be used for low-power photo-micrography.

When a large image is needed on the plate, as in making close-ups, there are two ways of making the frame move towards the subject. The first is to use a lens of short or moderate focus and move the lens and plate bodily towards the subject. The second is to use a long focus lens, when the increased distance from the rear nodal point to the plate correspondingly throws the perspective frame forward.

The first method can only be used easily when the subject to be photographed is flat or without much depth and relief. Moving the lens forward means that the view-point at the forward nodal point also moves forward, and the

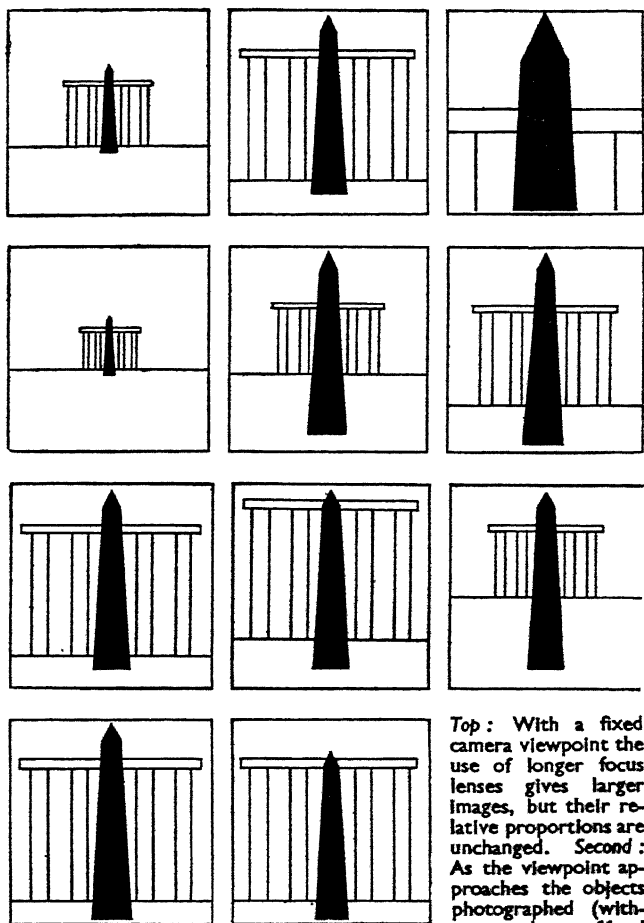


Top : As the focal length of a lens increases the sensitive plate or film and the perspective frame both move away from the nodal points. The pattern traced by rays on the perspective frame and the image on the plate both increase in size (pp. 36 and 37).

Lower : When lenses of different focal lengths view a scene from the same point of view (i.e., the forward nodal point N1), the images they produce give objects (A and B) in the same relative proportions, but on different scales (pp. 36, 37).

Third and bottom diagrams : When the point of view N1 moves away from the scene the images of two equal objects tend to become more nearly the same size, i.e., the relative proportions change (pp. 36, 37).

PERSPECTIVE



Top : With a fixed camera viewpoint the use of longer focus lenses gives larger images, but their relative proportions are unchanged. Second : As the viewpoint approaches the objects photographed (without any change of focal

length) proportions change rapidly. Third : The proportions of a scene can be changed at will by properly adjusting the taking distance and focal length. Centre (compared with the left) the distance and the focal length have been doubled. Right, taking distance and focal length have been halved. Bottom : Again by adjusting focal length and distance the proportions may be changed without affecting background size (pp. 36, 37).

usual difficulties are then met of exaggerated perspective, with outsize noses, outlandish limbs and the like.

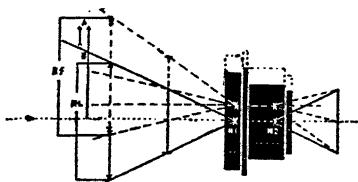
The second method is usually the best. With a long focus lens the perspective frame moves forward, but the viewpoint at the forward nodal point remains at a safe distance from the subject and there is not the same danger of exaggerated perspective.

There is one further point worth noting. It has just been explained why it is better to use a long focus lens for close-up work, and the above discussion and argument is applicable even when the close-ups are in the nature of table-top photography. When close-ups are required out of doors a form of lens that is very useful indeed is a telephoto lens (page 195). But if a telephoto lens is used for table-top work special attention must be paid to the position of the forward nodal point which is usually at a considerable distance in front of the lens. Telephoto lenses are dealt with in detail in another chapter, but the diagram on p. 199 will give a general idea of the positions of the nodal points of such a lens. The case drawn is that for a telephoto effect of 2X. In actual work of this type, of course, the focusing and composition are best done on a ground glass screen, but time and trouble are saved if it is remembered that the point of view from which a telephoto lens sees the picture is away out in front of it. There is no need to make any special point of this if the long focus lens used is of a standard anastigmat construction, as in this case the forward nodal point is not very far inside the lens from the front glass.

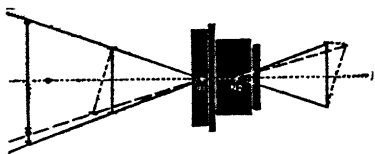
Rising Front and Swinging Back

In the case of a rising front the picture seen by the camera lens, and reproduced by it on the sensitive plate, is obtained merely by raising the perspective frame relative to the lens through exactly the same height as the lens has been raised by the movement of the front. If the lens moves upwards through a distance of half an inch, then the viewpoint from which the lens sees the picture, namely the forward nodal point, moves upwards through half an inch. The perspective frame moves upwards with the lens through the half inch, but does not stop there. It moves a further half inch to take into account the amount by which the lens axis is offset from the centre of the plate. This is shown on p. 41. Except in close-up work, where actually there is no need of a rising front, the effect of the movement of the nodal point is absolutely negligible compared with the relative shift of the perspective frame. It is this relative shift that brings into the picture features that would otherwise be left out. This is also brought out on p. 41.

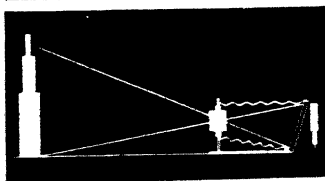
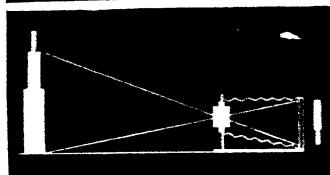
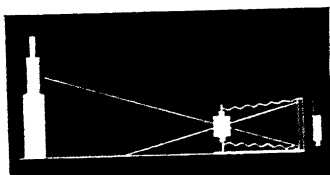
With a swinging back (or in exactly the same way with a swinging front) on the camera the picture thrown on the plate is that seen by an eye at the forward nodal point enclosed by a perspective frame that has been swung through an angle. That angle is equal to the angle through which the back has been swung, and is in the same direction. This is shown in detail on p. 41. The images on the sensitive material are covered by the frame turned through this angle.



Left : The use of a rising front implies a movement of the perspective frame relative to the lens (page 40).



Lower : A rotation of the perspective frame results from using a swinging back (page 40).



Right : The use of either a rising front or swinging back means that unwanted foreground gives way to parts of the picture otherwise outside the field of view.

This effect is not so simple In the case of a swinging back as in this case a type of distortion is introduced in which lines which should be parallel on the plate are found to be converging towards one another. The effect is specially evident in the convergence of the perpendicular edges of buildings (p. 317).

RISING FRONT AND SWINGING BACK

The Panorama Camera

To close this section reference should be made to the panorama camera. This type of camera, while it is by no means new, and not a particularly fashionable type of instrument, deserves mention for the ingenuity of its construction and method of working.

A good working rule for a normal lens is to assume that the diagonal of the plate covered is equal to the focal length of the lens, except of course if the lens is specifically stated to be intended for cine-film or miniature work. With a wide-angle lens a rough figure is to take the diagonal as twice the focal length. In the special case where a wider angle is required, and especially where the picture required is long and narrow, the panorama camera may be used. The principle of it is as follows :

It was explained fully, in the section dealing with finding the position of a nodal point, that if a lens is rotating about an axis through its rear nodal point, then there is no displacement of the image of a distant point caused by this rotation.

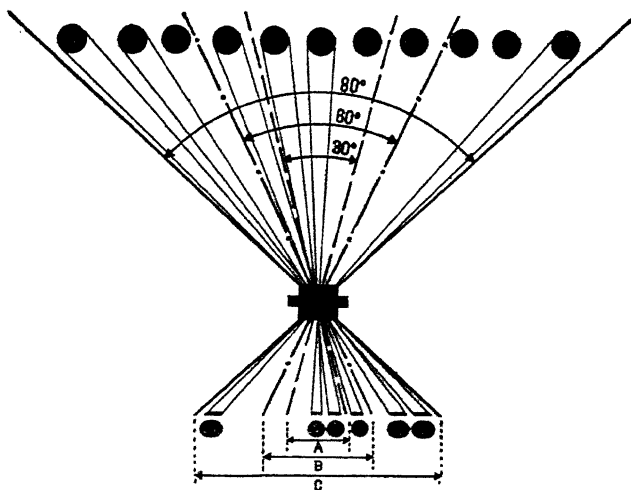
Now consider a lens covering a small field, as shown on p. 43, and forming an image of an infinitely distant, or comparatively distant, scene. The lens can rotate about an axis through its rear nodal point.

Suppose further that the sensitive film is a strip of film wrapped round part of the circumference of a drum, whose centre is at the rear nodal point of the lens. The radius of the drum is equal to the equivalent focal length of the lens. The arrangement is shown on p. 43.

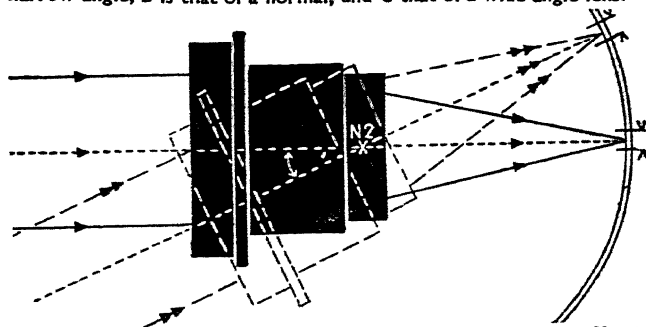
Owing to the small area covered by the lens in this special case there is no appreciable difference between a plane and a small element of the drum locating the film. A sharp image of that part of the distant field covered by the lens is thus formed on the curved film. As the lens swings round, pivoting about its rear nodal point, there is no shift of the image of a particular element of the scene. For a while, as long as it is in the restricted field of view of the lens, an element of the picture transmits light through the lens to a definite point on the film. As the lens swings round some parts of the picture go out of the field of view and others come in, as shown also on p. 43. The fact that the film is wrapped round a drum of the proper radius means that the image stays in focus throughout the course of the movement of the lens. There is, of course, no movement of the film.

The angle of view of the camera depends, not on the optical characteristics of the lens, but on the angle through which it can swing about its rear nodal point, and the length of film that is stretched along the drum. In all other cameras the angle of view is conditioned practically entirely by the optical characteristics of the lens, and the field over which the lens will give good definition and even illumination. These are dealt with in a later chapter.

While this type of camera is interesting from a theoretical point of view, and while it is useful in that it helps to emphasise the importance of the nodal points, in actual practice at the present day it is restricted to a few very highly specialised jobs, and it would be out of place to give any further and more detailed account of it here.



At the edges of the field of a wide-angle lens the images of cylindrical and spherical objects are unduly drawn out. A is the field covered by a narrow angle, B is that of a normal, and C that of a wide-angle lens.



In the panorama camera the lens covers only a small field. The film is wrapped on a drum with its centre at the nodal point N_2 of the lens and the lens pivots about this point. As the lens swings round different parts of the field come into view. Since the film is wrapped on a drum, images of objects contained in one plane are smaller at the ends of the film than they should be and images of horizontal lines in an object plane are curved. When photographing groups of people, the magnification between image and object can be made constant throughout the field by arranging the group along the circumference of a circle whose centre is at the camera.

WIDE-ANGLE LENS AND PANORAMA CAMERA

Angle of View

One topic allied to the perspective furnished by a lens is the angle of view of the lens.

The angle of view of the lens is the angle between the most widely separated rays that can be usefully recorded on a plate, that go to a light patch sufficiently small and bright to be useful. Or looked at from another point of view, the angle of view is the angle between the rays that go to opposite corners of a plate which has a sufficiently good definition over the whole of its area.

From what has been said above the logical points from which to draw these limiting rays are the forward and rear nodal points. Hence the definition of the angle of view can be more completely stated as this : Draw lines from the rear nodal point to the opposite corners of the plate used. The angle between these lines is the angle of view of the lens.

There are one or two points to notice in connection with this definition. In the first place the distance of the rear nodal point from the plate depends on the distance of the object on which the lens is focused and the corresponding shift of the lens to get a sharp focus. As a result the angle between the lines depends on the distance of the plate from the rear nodal point, and is a maximum when the lens is focused on an infinitely distant object, and the plate is at a minimum distance from the nodal point. Unless any special proviso is made it can be taken for granted that it is this maximum angle that is referred to as the angle of view.

In the second place a clear distinction must be made between the total angle of view just described, and what is often stated, namely the semi-angle of view. This is half the above angle, and it is the angle between one of the lines described above and the line joining the nodal point and the centre of the negative, i.e., the lens axis.

Table I gives the diagonal plate covered by a lens of 1" focus in terms of the angle of view of the lens. To get the diagonal covered by a lens of greater focal length, 4" say, merely requires the multiplication of the figures given by 4.

1.---DIAGONALS COVERED AND FIELDS IN DEGREES

| Field in Degrees | 8 | 10 | 12 | 14 | 16 | 18 | 20 | 22 | 24 | 26 | 28 | 30 |
|---------------------------------------|------|-------|-------|------|------|------|-------|-------|-------|-------|------|-------|
| Diagonal (in inches) for 1" focus ... | 9/64 | 11/64 | 13/64 | 1/4 | 9/32 | 5/16 | 11/16 | 25/64 | 27/64 | 15/32 | 1/2 | 17/32 |
| Diagonal (in mm.) for 1 cm. focus... | 1.40 | 1.75 | 2.10 | 2.46 | 2.81 | 3.17 | 3.52 | 3.89 | 4.25 | 4.62 | 4.99 | 5.36 |

| Field in Degrees | 32 | 34 | 36 | 38 | 40 | 42 | 44 | 46 | 48 | 50 | 52 | 54 |
|---------------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|--------|
| Diagonal (in inches) for 1" focus ... | 37/64 | 39/64 | 21/32 | 11/16 | 23/32 | 49/64 | 13/16 | 27/32 | 57/64 | 15/16 | 31/32 | 1 1/64 |
| Diagonal (in mm.) for 1 cm. focus... | 5.73 | 6.11 | 6.50 | 6.89 | 7.28 | 7.68 | 8.08 | 8.49 | 8.90 | 9.32 | 9.75 | 10.19 |

| Field In Degrees | 56 | 58 | 60 | 65 | 70 | 75 | 80 | 85 | 90 | 95 | 100 | 110 |
|-----------------------------------|-------|-------|-------|-------|---------|---------|---------|---------|------|--------|-------|---------|
| Diagonal (in inches) for 1" focus | 1.16 | 1.764 | 1.532 | 1.932 | 1.13/32 | 1.17/32 | 1.43/64 | 1.53/64 | 2 | 2.3/16 | 2 1/2 | 2.27/32 |
| Diagonal (in mm.) for 1 cm. focus | 10.63 | 11.09 | 11.55 | 12.74 | 4.00 | 5.35 | 6.78 | 18.33 | 20.0 | 21.82 | 23.84 | 28.56 |

The field in degrees is the angle between the extreme rays that can be usefully recorded on the plate. Normally these go to the opposite corners of the plate or film frame. The diagonal of this latter depends on the focal length of the lens used and is obtained by scaling up the values given above.

by scaling up the values given above, e.g., a 4" focus lens covers a field of 44 degrees, then the diagonal is $4 \times 13/16 = 13/4 = 3\frac{3}{4}$ ", alternatively the diagonal covered is $4 \times .808 = 3.232$ inches, i.e., approximately $3\frac{1}{4}$ inches, to within sufficiently close limits.

is $4 \times 4.806 = 3.932$ inches, i.e., approximately $3\frac{1}{2}$ inches, to within sufficiently close limits.

| | | | | | | | | |
|-----------------------|---------|---------|---------|--------|---------|---------|---------|---------|
| Flange size in inches | 1 x 1½ | 1½ x 2½ | 1½ x 2½ | 2 x 3 | 2½ x 3½ | 2½ x 4½ | 3½ x 3½ | 3½ x 4½ |
| Diagonal in inches | 1 13/16 | 2 1/16 | 3 | 3 3/16 | 3 15/16 | 4 1/16 | 4 13/16 | 5 5/16 |

| | | | | | | | | | | | |
|---------------------|---------|---------|--------|--------|---------|-------|----------|--------|----------|---------|---------|
| Film size in inches | 2½ × 4½ | 3½ × 5½ | 4 × 5 | 4 × 6 | 4½ × 6½ | 5 × 7 | 6½ × 8½ | 5 × 8 | 8 × 10 | 10 × 12 | 12 × 15 |
| Diagonal in inches | 5 11/16 | 6½ | 6 7/16 | 7 3/16 | 8 1/16 | 8½ | 10 11/16 | 9 7/16 | 12 13/16 | 15½ | 19½ |

| | | | | | | | | | | | | | | |
|-------------------|---------|----------|-----------|-----------|-----------|--------|--------|-------|--------|-------|---------|---------|--------|--------|
| Film size in cms. | 375 x 5 | .65 x .9 | .75 x 1.0 | 1.8 x 2.4 | 2.4 x 3.6 | 4 x 6† | 5 x 7† | 6 x 6 | 4† x 6 | 6 x 9 | 8 x 10† | 6† x 11 | 9 x 12 | 8 x 14 |
| Diagonal in cms. | .625 | 1.11 | 1.25 | 3.0 | 4.33 | 7.63 | 9.01 | 8.48 | 7.5 | 10.82 | 13.20 | 12.77 | 15 | 16.12 |

| | | | | | | | |
|-------------------|----------|----------|-----------|-----------|----------|---------|---------|
| Film size in cms. | 10 × 12½ | 12 × 16½ | 12½ × 17½ | 16½ × 21½ | 12½ × 20 | 20 × 25 | 25 × 30 |
| Diagonal in cms. | 16.0 | 20.4 | 21.52 | 27.1 | 21.36 | 32.0 | 39.05 |

The Positions of Object and Image

So far the positions of an object and the corresponding image relative to the lens have been discussed fully only for one particular case.

When the object is at an infinite distance in front of the lens, and so at an infinite distance in front of the forward nodal point, the image is in the rear focal plane. In other words, the distance from the rear nodal point to the image position is equal to the equivalent focal length of the lens. In fact it defines the equivalent focal length.

There are cases of equal importance, however, especially in enlarging work, where the distance of the object from the front of the lens is quite small. The method of finding the image position in these circumstances, of working out how it lies relative to the lens, is the next subject to be tackled.

There are two main forms which the formulæ relating the object and image positions can take. One is most suitable for dealing with such things as getting an idea of the size and arrangement of a focusing scale. The other is more of service when dealing with enlarging and projection problems.

Consider form number one first.

All distances of the object are measured from the forward nodal point in the direction of the arrow as shown on page 47. The distance of the object from the forward nodal point is denoted by u .

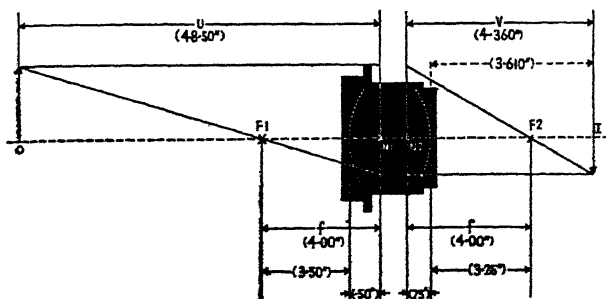
In the same way the distances of the corresponding image positions are taken from the rear nodal point, and are denoted by v .

The equivalent focal length of the lens is denoted by f . f is positive when the lens is converging, as already explained on page 27.

The basic formula is—

$$\frac{1}{u} + \frac{1}{v} = \frac{1}{f}$$

which can be put in two other convenient forms



The positions of the focal and nodal points for a typical lens are shown, and the way in which the object and image distances U and V are measured from the nodal points or principal planes (p. 46).

The distance of the object U is measured from the forward principal plane, and that of the image V from the rear principal plane (p. 46).

The distance of the forward focal point $F1$ from the forward nodal point $N1$ is the same as the distance of the rear focal point $F2$ from the rear nodal point $N2$, and is the *focal length* of the lens (p. 27).

Incidentally this diagram shows how the position of an image can be found by drawing two rays. The image of the object shown at O is at right angles to the lens axis through a point I which is to be found. From the end of the object through O two rays are drawn to meet the principal plane through $N1$. One ray is parallel to the axis and the other goes through the forward focal point $F1$. The corresponding rays are so directed that they cut the principal plane through $N2$ at the same heights as the rays from which they are derived cut the plane through $N1$. This fixes one point on each ray. Now consider the ray drawn parallel to the lens axis. The corresponding ray must go through the rear focal point $F2$. Two points on this ray are now known and so the ray can be drawn. Similarly the ray corresponding to that drawn through the forward focal point emerges parallel to the lens axis, and so it can be drawn through the point already fixed on the rear principal plane. The intersection of these two emergent rays gives the position of the end of the image. Note that the image is inverted.

OBJECT AND IMAGE POSITIONS

$$v = \frac{u \times f}{u - f}, \text{ or } u = \frac{v \times f}{v - f}$$

A concrete example or two will show how these formulæ are to be used.

Suppose that some work is to be done with a lens of 4 inches focal length, and that the nominal figure of 4 inches coincides with the actual equivalent focal length. Unless it has been produced to lie within certain limits definitely specified, it is a fairly safe assumption to make that a lens of nominally 4 inches focal length will have an equivalent focal length between 3.96 and 4.04 inches.

The first thing to do is to locate the positions of the nodal points. A method has been described on p. 30 that is mainly applicable to cases where the focal length has to be measured. If the focal length is known with sufficient accuracy, for instance if it is taken from the values engraved on the lens, or if it has been measured by one of the methods explained on pp. 33-35 a simpler procedure can be followed. The lens is focused on an object at a thousand yards or more, and the back focal length of the lens found. Suppose that this is 3.25 inches. The lens is then turned round, stopped down if necessary to get sharp definition, and the back focus of the reversed lens is found. Suppose that this is 3.50 inches. Then the positions of the nodal points are as shown on p. 47.

If an object is at 4 feet in front of the foremost lens surface, then it is $48.00 + .50 = 48.50$ inches in front of the forward nodal point, as shown on p. 47, i.e., $u = 48.50$. Remembering that $f = 4.00$ inches, and using the formula—

$$v = \frac{u \times f}{u - f}$$

$$\text{then } v = \frac{48.50 \times 4.00}{48.50 - 4.00} = \frac{194.0}{44.50} = 4.360 \text{ inches, to the nearest } .001 \text{ inch.}$$

The image is 4.360 inches from the rear nodal point, and so is $4.360 - .750 = 3.610$ inches from the rearmost surface of the lens, as shown on p. 47.

Suppose that with the same lens an image is formed 3.500 inches from the rearmost surface of the lens, then it is $3.500 + .750 = 4.250$ inches from the rear nodal point, i.e., $v = 4.250$ inches. Using the formula—

$$u = \frac{v \times f}{v - f}$$

$$\text{then } u = \frac{4.250 \times 4.00}{4.250 - 4.00} = \frac{17.00}{.250} = 68.00 \text{ inches.}$$

The object that gives an image in this position is 68.00 inches in front of the forward nodal point, and so $68.00 - .50 = 5 \text{ feet } 7\frac{1}{2} \text{ inches}$ in front of the foremost surface of the lens.

Some typical examples of the use of these formulæ are found in calculations concerning focusing scales, and examples of their employment in dealing with questions

arising in this work are given below. The examples are for the lens already discussed, whose nodal points are shown on p. 47.

Focusing Travel

1. The first type of question is this : how long must be the focusing travel of a lens if it is to focus from infinity down to 4 feet, say. The lens has an equivalent focal length of 4.00 inches.

When the object is at infinity the image is in the rear focal plane, and

$$v = 4.000 \text{ inches.}$$

A calculation of the first type on page 48 for 48.5 inches gives the image position for an object at 4 feet., i.e., $48 + .5$ inches from the forward nodal point.

Namely with $u = 48.50$. $v = 4.360$ inches.

The focusing travel in this case is .360 inches. If the upper limit is, say, 50 feet, and not infinity the calculation is done for $50 \times 12 + .5 = 600.5$ inches, and the v worked for this value of u . The focusing travel is then obtained straightforwardly for this upper limit of distance.

It should be noted that in this case there is really no need to know the position of the rear nodal point. For many practical purposes there is no need either to know the position of the forward nodal point. In the majority of lens constructions it is not far removed from the foremost surface of the lens, half an inch in the present instance. And there is not a very appreciable difference between 3 feet $11\frac{1}{2}$ inches and 4 feet when it comes to focusing a lens, so no appreciable error is made if the distance from the forward nodal point is taken to be 48.00 inches. In this particular case it makes a difference of .004 inches in the lens position. For distances greater than 4 feet the error is even less. Where pedantic accuracy is needed the extra half inch must be taken into account. But where common-sense accuracy is enough the distance of the forward nodal point from the foremost lens surface can be neglected.

Increasing the Focusing Range

2. The second type of question is met with when a lens is fitted to a camera with a restricted focusing range. Suppose that a 4 inch lens is fitted and the camera is designed to give enough travel of the lens so that it will focus down to 6 feet. By fitting an adaptor the lens can be made to focus down to 3 feet. The question is : what must be the thickness of this adaptor, and what focusing range will be provided for by the lens travel possible with the design of camera ?

A calculation of the type just described shows that with

$$u = \text{infinity} \quad v = 4.000 \text{ inches.}$$

$$u = 72.50 \text{ inches. } v = 4.233 \text{ inches.}$$

and so the lens travel provided is .233 inches.

$$\text{With } u = 36.50 \text{ inches. } v = 4.492 \text{ inches.}$$

Then the thickness of the adaptor to take the lens a maximum distance of 4.492 inches away from the plate is $.492 - .233 \text{ inches} = .259 \text{ inches}$.

With the existing focusing travel the minimum distance from the plate is $4.492 - .233 = 4.259 \text{ inches}$, i.e., $v = 4.259 \text{ inches}$. Using the formula—

$$u = \frac{v \times f}{v - f}$$

then the corresponding object distance is, for $v = 4.259 \text{ inches}$

$$u = \frac{4.259 \times 4}{4.259 - 4} = \frac{17.036}{.259} = 65.8 \text{ inches to the nearest .1 inch.}$$

And so with an adaptor of this thickness the lens will focus from 3 feet to $65.8 - .5 = 65.3 \text{ inches}$.

$$\text{A rearrangement of the above formulæ gives } T = \frac{f^2}{u - f}$$

where T is the focusing travel.

In the example on page 49,

$$T = \frac{4 \times 4}{48.5 - 4} = \frac{16}{44.5} = .360 \text{ inches}$$

The focusing scales on some cameras refer to distances measured from the focal plane. In these cases

$$T = \frac{f^2}{D - v - f}$$

where D is the distance of the object from the focal plane. For most practical purposes this may be simplified to

$$T = \frac{f^2}{D - 2f}$$

When a lens has to focus an object inside the nearest point of its normal range either an adaptor can be used as just described above, or else a supplementary lens (see below) can be used, and in fact a supplementary lens is more commonly used.

Supplementary Lens and Its Focusing Range

3. Suppose for instance, that in place of an adaptor as just described a supplementary lens is used to give the same focusing distance with the same lens.

A supplementary lens is usually a simple thin lens and is fitted immediately in front of the lens with which it is used, so that the distance between the nodal points of the supplementary lens can be neglected, and so can the distance between these nodal points and the foremost lens surface. The arrangement of the supplementary lens is shown on p. 53, but the relative distance between the supplementary lens and the foremost lens surface is exaggerated.

The camera lens in its focusing mount is set for infinity. In the present case the equivalent focal length of the thin supplementary lens is 36 inches. With the object at 36 inches in front of the lens the rays that emerge from the supplementary lens are all parallel, as shown on p. 53, as if they came from an object at infinity. These rays are picked up by the camera lens which is set to focus parallel rays at its infinity setting, and brought to a sharp focus on the film.

The question that then arises is : what focusing range is possible with the existing lens movement, and how does it compare with the range just worked out above for the case where an adaptor is used.

The answer to this is interesting among other things in that it explains what happens when one of the formulæ on page 48 gives a negative number.

The existing lens travel is enough to bring to a sharp focus rays coming from a point six feet in front of the foremost lens surface. The nearest object, that can be focused with the supplementary lens, is thus one that will have the light rays it sends out bent by the supplementary lens, so that they appear to come from an object six feet in front of the lens in the camera.

Call the u and v for the particular case where the lens that is being dealt with is a supplementary lens $u(s)$ and $v(s)$ respectively. Now, remembering what has just been said about the positions of the nodal points of the thin supplementary lens, and remembering that u and v are measured as being positive quantities in the directions of the arrows on p. 47, then what we require is that $v(s) = -72$ inches, as shown on p. 53.

When u and v are negative all that this means is that they are on the opposite sides of the nodal points to their usual positions.

If $v(s) = +72$ inches the rays from the supplementary lens converge to a point 6 feet behind the rear nodal point of the supplementary lens, and so 6 feet behind the foremost lens surface. With $v(s) = -72$, as it is here, the rays of light from the supplementary lens seem to diverge from a point six feet in front of the foremost lens surface, as shown on p. 53.

Putting $v(s) = -72$ in the formula, and remembering that $f(s) = 36$ inches

$$u(s) = \frac{v(s) \times f(s)}{v(s) - f(s)}$$

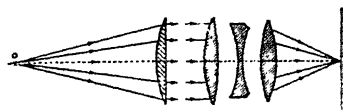
$$\text{then } u(s) = \frac{(-72) \times 36}{(-72) - 36} = \frac{-(72 \times 36)}{-(72 + 36)} = \frac{(72 \times 36)}{(72 + 36)}$$

$$= \frac{72 \times 36}{108} = 24 \text{ inches}$$

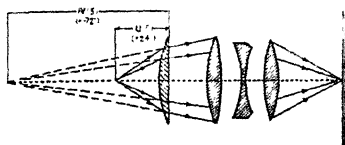
and so with the supplementary lens in position the camera can focus from 3 feet down to 2 feet.

With an adaptor to take the lens focusing down to 2 feet, instead of the 3 feet, for which a calculation was done above, the focusing range for the same lens is from 2 feet $9\frac{1}{2}$ inches down to 2 feet, so that from the point of view of focusing range there is little to choose between the two methods of getting down to close work. As a rule it is a simpler job to fit a supplementary lens in the same way that a filter is fitted on to the front of the lens. And in fact this is the only way when a between lens shutter is fitted.

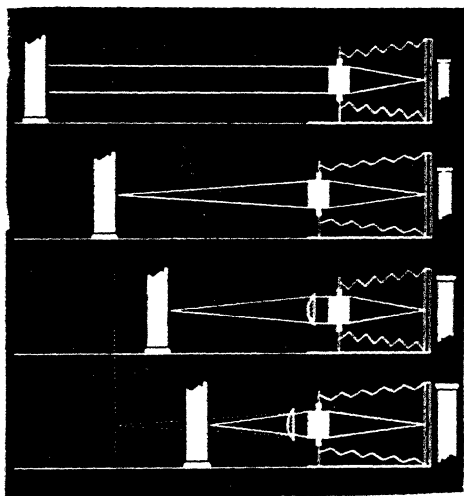
From the point of view of optical quality there is no general ruling to be made. Everything depends on the individual lens



Left : The rays from a point are made parallel by a supplementary lens before falling on a camera lens focused for infinity.



Lower : Rays from a point nearer to the supplementary lens than the focal point of this latter. They emerge from it diverging from a point in front of the lens. The rays can only be brought to a focus on the sensitive material if the unaided camera lens can focus on this point from which they diverge



Above : By extending the camera bellows and by using a supplementary lens, an object can be focused at shorter distances and larger images of it produced. The smallest image of an object is formed when the camera is focused for infinity (top). By extending the bellows the camera can be focused at a viewpoint nearer the object and a larger image obtained (second diagram). A still larger image results from the use of a supplementary lens and a camera focused for infinity (third diagram), and the largest possible image is given when (bottom) the use of a supplementary lens and the maximum bellows extension allows of the closest approach to the object (p. 51).

SUPPLEMENTARY LENSES

and the way in which the correction of its aberrations is maintained down to these short distances, and the comparative effect of new aberrations then introduced compared with those introduced by the supplementary lens. This will be clearer after the account of lens aberrations given in the next chapter. With a supplementary lens used in this way the f /number of the combination is just that of the camera lens, and this value is to be used in working out exposure times.

Enlarging and Projection Formulæ

The other fundamental lens formula is specially of use when dealing with enlarging and projection problems.

Suppose that a picture is being projected from a negative behind the lens to an enlarging board in front of the lens. Call the position of the negative the projection position, and the position of the board the enlarging position, as shown on p. 55.

As before the distance of the enlarging position in front of the forward nodal point of the lens is u , and the distance of the projection position behind the rear nodal point is v .

The picture on the enlarging board is exactly that carried by the negative but on a larger scale. The scale of the enlarged picture relative to the negative picture is the "magnification" of the arrangement, and is denoted by M .

When $M = 2$ then every length in the enlarged picture is twice the corresponding length on the negative. When $M = \frac{1}{2}$ then every length in the projected picture is only half the length of the corresponding part of the negative picture, and instead of enlarging, the process for which the lens is being used is copying on a reduced scale.

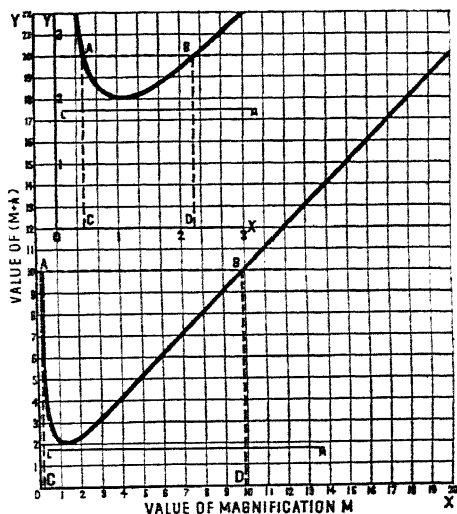
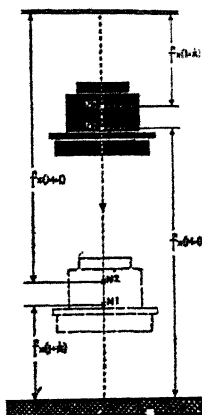
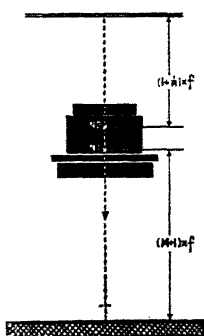
It will save time if we talk throughout of enlarging, and set up the convention that when M is less than one it is—strictly speaking—reducing and not enlarging that is meant.

The focal length of the lens is f . Then the fundamental formulæ are—

$$u = (M + 1) \times f; \quad v = \left(1 + \frac{1}{M}\right) \times f$$

as is shown on p. 55.

Right : The relative positions of negative and enlarging board are shown when an M -fold enlargement is produced. The distance of the back nodal point from the negative is $f \times (M+1) \div M$ and that of the forward nodal point from the enlarging board is $f \times (M+1)$, where f is the focal length of the enlarger lens (p. 54).



Above : With a given separation of negative and enlarging board there are in general two lens positions when a sharp image is formed on the enlarging board, in one case an enlarged image, in the other a reduced image (p. 57).

Left : From the graph the values of the magnification M (one corresponding to enlargement, the other to reduction) are obtained when

$$M + \frac{1}{M}$$

is known. A horizontal line is drawn, such as AB corresponding to that value and vertical lines drawn through the points where it cuts the curve. The positions where these cut the horizontal scales give the two possible values of the magnification for the set-up. If the line does not cut the curve the set-up is physically impossible (p. 57).

ENLARGING LENS SETTINGS

Neglecting the separation between the nodal points of the lens the overall length from projection to enlarging positions is—

$$(M + \frac{1}{M} + 2) \times f.$$

In actual practice the separation between the nodal points has to be added on to this overall length, but in many cases it gives only a small correction ; on the average much less than .15f.

Two examples of the use of these formulæ are given below—

Maximum Enlargement

1. Suppose that with the 4 inch lens already described, and illustrated on p. 55, the separation of the nodal points is one inch, and that when the lens is used in an enlarger the way in which this latter is built means that the greatest distance from the projection position to the enlarging position is 49 inches. What is the maximum degree of enlargement permitted in this enlarger?

Using the fact that the length overall from projection position to enlarging position is

$$(M + \frac{1}{M} + 2) \times$$

plus the separation of the nodal points, then

$$(M + \frac{1}{M} + 2) \times 4.00 + 1 = 49 \text{ inches}$$

$$\text{and so } (M + \frac{1}{M} + 2) = \frac{49 - 1}{4} = 12$$

$$\text{i.e., } M + \frac{1}{M} = 10.$$

To get the value of M from this formula means solving a quadratic equation or finding it from the graph drawn on p. 55. The second is much the simpler as a rule for the range covered by the graph, i.e., up to $M = 10$.

Values of M are measured off from left to right, and the values of

$$M + \frac{1}{M}$$

corresponding to these are measured vertically. To get the correct value of M all that is needed is to draw a line at the correct height, in this case 10 units above the base line OX to cut the graph. This it does in two points marked A and B on p. 55. Draw lines from A and B , namely AC and BD parallel to the side line OY to cut the base line OX in C and D . The positions of C and D give the possible values of M .

For every set up, with a given distance between projection and enlarging positions, there are two lens positions when the two positions

are mutually in focus, corresponding to enlarging and reducing, as shown on p. 55. Corresponding to this there are the two values of M found as described above, one greater than one, and the other less than one, representing enlarging and reducing respectively.

When it happens that $M=1$ the two magnifications given by the above procedure are the same and the lens has only one position. It is then giving a 1 : 1 enlargement or reduction. When the line drawn parallel to the base line fails to cut the curve as shown by the line LM , then the physical set up is impossible. The projection and enlarging positions are too near together to be able to focus with the lens of the given focus.

In the case drawn on p. 55, the values of M are 9.899 and .101, and so the maximum enlargement possible with the arrangement provided is near enough 9.9, or for all practical intents and purposes the magnification is 10 times. Using the formulæ :-

$$u = (M+1) \times f \quad \text{and} \quad v = (1 + \frac{1}{M}) \times f$$

then sufficiently near for all practical purposes in this case,

$$u = (10 + 1) \times f = 44 \text{ inches} \quad v = (1 + \frac{1}{10}) \times f = 4.4 \text{ inches,}$$

and using the data about the nodal points of this lens, already given on p. 47, the exact enlarger arrangement follows immediately.

The main use of the graph is in determining enlarger arrangements for small degrees of enlargement. An approximate formula can be arrived at in this way :

Take the distance from the negative to the enlarging board and subtract from this the separation of the nodes in the lens. (A rough figure for this separation is .15 of the focal length of the lens). Call this the "effective distance." Then the formula is

$$\text{Degree of Enlargement} = (\text{Effective distance}) \div (\text{Focal length}) \text{ less } 2.$$

2. Thus if the effective distance is 48 inches, and the focal length 4 inches, then the degree of enlargement $= 48 \div 4 - 2 = 12 - 2 = 10$.

This formula gives an error of 1% in the value of the magnification when this is 10 or thereabouts, of 4% when the magnification is 5, and of 10% when the magnification is 3.2.

It is rarely, if ever, necessary to get the magnification correct to within less than 1%, and so for values of M greater than 10 the approximate formula just given can be used. The value of M so obtained can be used immediately in the determination of u and v by the formulæ given, the error in u is negligible, that in v is less than 1% when the enlargement is more than 10 fold.

Focal Length of Projection Lens

Another example of the use of these formulæ is in answering a question often asked by miniature camera workers : some 35 mm. slides are to be projected in a miniature projector to give a picture 3 feet \times 4½ feet.

The length of the room in which the demonstration is to take place is 15 feet. What focal length of lens is needed to give the required size of projection?

The pedantic way is to proceed exactly as was done for an enlarging problem above, except that in this case M is known and f has to be worked out. But for practical purposes it is quite accurate enough to proceed on slightly more simple lines. Call the distance of the front of the lens from the projection screen u . Actually, of course, u is the distance of the screen from the forward nodal point, but the error introduced in the calculation by measuring it from the front of the lens is negligible as a rule.

Then use the formula

$$u = (M + 1) \times f.$$

In the case quoted the magnification required is $(54 \times 2.54) \div 3.6$, since the longer side of the projected picture is to be 54 inches, i.e. 54×2.54 cms; and the longer side of the picture frame of the miniature slide is 3.6 cms. The magnification m works out to be $M = 38.1$, and $M + 1 = 39.1$. It can safely be assumed that with a room 15 feet long the maximum distance of the screen from the front of the lens will be 13 feet, i.e., 156 inches. Then—

$$156 = 39.1 \times f \text{ and } f = 4.00 \text{ inches to the nearest .01 inch.}$$

A 4 inch lens in the case quoted will just give the size of picture required, and as it happens this is about the minimum focal length of simple projection lens that will handle this size of slide. If a shorter focal length is needed to cover a miniature slide, then a lens of anastigmat rather than true projection form, must be used. This is dealt with more especially on page 144.

The final formula needs only brief mention. It serves to relate the two classes of formulæ used, viz. :

$$\frac{1}{u} + \frac{1}{v} = \frac{1}{f}$$

$$\text{and } u = (M + 1) \times f, \quad v = \left(1 + \frac{1}{M}\right) \times f$$

already used and described. It is

$$M = u \div v.$$

In this case the object distance u is the distance of the screen, and the image distance is taken as the distance of the slide, both measured from the lens, since the screen is "in front," and the slide "behind" it.

Definition in Depth

When dealing with lenses from the point of view of the previous section, that is to say from the point of view of the position of an object and the position and size of its related image, the only concern is with the plane where an absolutely perfectly sharp image is formed.

No fault can be found with such an image no matter how high a standard is set. And when a reasonably high standard of reproduction is required no fault can be found with the images given by objects slightly near and farther than the object in sharp focus. The images produced are slightly out of focus, and they fail when judged by the criterion of absolute perfection, but by a reasonably high and critical standard they are of acceptable sharpness and quality.

This general fact, that images produced by a lens may be of acceptable crispness even when they are slightly out of focus, is referred to as the "depth of focus" or "depth of field."

In optical terminology the term *depth of focus* means the total allowable variation of the sensitive surface from the position of best focus within which the image is tolerably sharp by a given standard. *Depth of field* means the difference between the object distances corresponding to these limits of sharpness in a given image plane. In the common parlance of photographers, the term *depth of focus* is sometimes used with both meanings interchangeably.

Criterion of Crispness

The first step in getting a quantitative estimate of the depth of field of a lens is to arrive at some conclusion about the size of a light patch that will give sufficiently good definition, assuming that the light patch is circular, i.e., that it is the so called *circle of confusion*.

The criterion generally accepted is that a circle of light one hundredth of an inch in diameter, viewed from a distance of ten inches, which is the average value of the closest distance down to which the adult eye can focus, is not distinguishable from a point.

Suppose that a lens of 4 inches focal length is being used and is focused on infinity, light from a point on the

lens axis at a nearer point is brought to a focus at a point farther away from the lens, and the rays coming from the lens thus form a circular light patch, as shown on p. 61, of diameter D inches.

It has already been explained, in the section dealing specially with perspective, that the lens views the scene from the forward nodal point, and sees it framed in an area the size and shape of the sensitive film or plate held at a distance of 4 inches from the forward nodal point. This is the impression recorded on the negative.

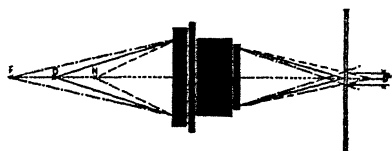
To see things as the lens sees them, and as an eye placed in the position of the lens would see them, means that the print should be viewed from a distance of 4 inches. The eye cannot focus down to this distance, without artificial aid such as the use of a magnifying glass (which incidentally acts for the eye in the same way that a supplementary lens acts for a camera lens, bringing its focusing range down to a new low value). To get the correct perspective either a magnifying glass must be used, or the print must be enlarged in the ratio of $10 \div 4$, i.e., $2\frac{1}{2}$ times and the enlargement viewed at a distance of ten inches, the closest distance to which the normal eye can focus. (Wrong perspective effects may become particularly noticeable with telephoto lenses—see p. 196.)

In any case the result is the same, the disc of light of diameter D from an out-of-focus point is enlarged two and a half times to a diameter of $2.5 \times D$ inches. Since the diameter of the disc is now to be .01 inch so that when viewed from a distance of ten inches it will be sufficiently small to seem a point, then

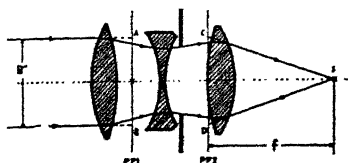
$$2\frac{1}{2} \times D = .01, \text{ i.e., } \frac{10 \times D}{4} = .01 \text{ inch.}$$

That is to say, when a lens of 4 inches focus is used the diameter of the out-of-focus disc must not exceed .004 inch.

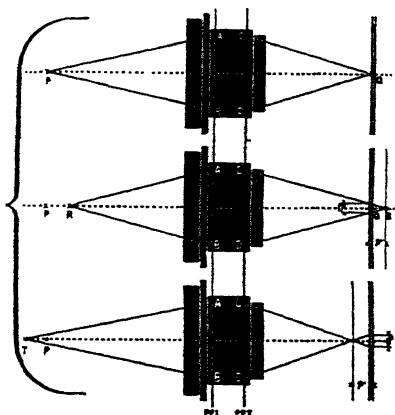
The same line of argument shows that when a lens is used whose focus is f inches, the diameter of the disc on the plate must not exceed



Top : Rays from the focused point *O* meet in a point on the sensitive material, rays from other points form a patch of light. Up to a certain limit of size the patch is indistinguishable from a point for practical purposes, and this leads to depth of field (p. 59).



Above: The f /number of the lens is the focus f divided by the diameter B of the largest parallel beam that gets through. The diameter of the beam is usually limited by a metal stop or iris diaphragm in the middle of the lens mount. As the diameter of this diaphragm opening decreases so does that of the beam of light it allows to pass and the f /number increases. The depth of field also increases (p. 62).



Above: The rays from the nearer point give a disc of light because they have not yet come to the focus when they meet the plate or film. Those from the farther point have passed through a focus already. When the point *P* is focused on the plate or film rays from the nearest limit of the depth of field *R* give a disc of specified diameter *D*, —that for practical purposes is accepted as sharp—and the same holds for the rays from the farthest limit *T* (p. 59).

DEPTH OF FIELD

$$\frac{f}{10} \times .01 \text{ inches, i.e., } f \times .001 \text{ inches.}$$

This is for the case when the lens is focused for infinity, and the distance of the plate from the back nodal point is equal to the focal length. When the lens is focused for any other distance the reasoning is exactly the same, but the formula for the allowable diameter of the disc is now

$$\frac{d}{10} \times .01 \text{ inches, i.e., } d \times .001 \text{ inches,}$$

where d is the distance of the plate from the rear nodal point.

f/Numbers

Before finding what lens position will give a disc of light of this size it is essential to specify what diameter of light beam is used to produce the image. This is best done by using the f /number of the lens.

In any actual lens the amount of light that goes through is limited by the edges of the lens and the metal work of the mount. The amount of light getting through depends on the actual path that the light takes inside the lens, and this depends in turn on the position of the object point from which it comes. When the object point is away from the lens axis the calculation of the amount of light going through is apt to be complicated. As a result the only straightforward way is to deal with the light passing power of a lens when the light is a parallel beam coming from a point at infinity on the lens axis. The amount passed through when the object point is nearer the lens, and still on the axis, is slightly less than the amount passed through by the lens when the object point is at infinity, but in dealing with depth of field this difference can be neglected.

When the light arriving at a lens is a parallel beam from a point at infinity the path of the largest diameter beam that gets through the stop is shown on p. 61. The beam goes into the lens aiming at the points A and B on the first principal plane (this is defined on page 26), and comes out of the

lens aiming away from the points C and D on the rear principal plane, as shown on p. 61.

The diameter of the parallel beam is B inches, the focal length of the lens is f inches. Then the f/number of the lens is $f \div B$. Thus if the lens is of 4 inches focus, and the diameter half an inch, then the lens is working at $f\ 4 \div \frac{1}{2} = f8$.

f/Numbers for Close-ups

The f/number of a lens measures its light-passing power. The smaller the f/number the greater the quantity of light concentrated in the image by the lens ; an f 2 lens concentrates 4 times as much as an f 4 lens, and twice as much as an f 2.8 lens. Hence, the smaller the f/number the shorter the exposure needed in any given set of lighting conditions.

The rule is : if we have two lenses, one working at f/n and the other at f/m, then the first concentrates $(m \div n)^2$ times as much light as the second. For instance if the first lens works at f 5.6, i.e., $n = 5.6$, and the second works at f 4, i.e., $m = 4$, then $m \div n = 4 \div 5.6 = .71$ (approximately), and $(m \div n)^2 = .71^2 = .5$ approximately. The first lens passes through only half as much light as the second.

The aperture of a lens is controlled by the way in which the leaves of an iris diaphragm open and close as a ring on the lens mount is turned, so allowing more or less light to get through. The calibrations of the ring are arranged so that in passing from one figure to the next the amount of light passed by the lens is halved. From f 2 to f 2.8 the light is halved ; similarly from f 2.8 to f 4 it is halved again.

This holds as long as the object to be photographed is at a distance from the lens more than about 10 times the focal length of the lens used. When the object is at a distance of S times the focal length of the lens the effective stop value or f/number is not that engraved on the lens mount, but is equal to this multiplied by $S \div (S - 1)$. Thus if a lens is used for copying work or close ups where $S = 3$, and the iris aperture is set at f 4, it is effectively working at $f\ 4 \times (3 \div 2)$

II.—HYPERFOCAL DISTANCES (IN FEET AND INCHES)

Aperture.

| Focal Length | f 1.5 | f 2.0 | f 2.5 | f 3.0 | f 3.5 | f 4.0 | f 4.5 | f 5.6 | f 6.3 | f 8 | f 11 | f 16 | f 22 | f 32 | f 45 |
|-------------------|-------|-------|-------|--------|-------|--------|-------|-------|-------|-------|-------|--------|-------|-------|-------|
| 1" 25 mm. ... | 55-6 | 41-9 | 33-4 | 27-9 | 23-10 | 20-10 | 18-6 | 14-8 | 13-4 | 10-5 | 7-6 | 5-3 | 3-9 | 2-7½ | 1-10½ |
| 1½" 28 mm. ... | 62-6 | 46-11 | 37-6 | 31-3 | 26-9 | 23-6 | 20-10 | 16-9 | 15-0 | 11-9 | 8-6 | 5-10½ | 4-3 | 2-11 | 2-1½ |
| 1½" 35 mm. ... | 76-6 | 57-4 | 45-10 | 38-3 | 32-9 | 28-8 | 25-6 | 20-6 | 18-4 | 14-4 | 10-5 | 7-2 | 5-3 | 3-7 | 2-7½ |
| 1½" 42.5 mm. ... | 90-4 | 67-9 | 54-3 | 45-1 | 38-9 | 33-11 | 30-1 | 24-2 | 21-8 | 17-0 | 12-4 | 8-6 | 6-2 | 4-3 | 3-1 |
| 2" 50 mm. ... | 111-0 | 83-6 | 66-8 | 55-6 | 47-7 | 41-9 | 37-1 | 29-9 | 26-8 | 20-11 | 15-1 | 10-6 | 7-6 | 5-3 | 3-9 |
| 2½" 62.5 mm. ... | 138-9 | 104-2 | 83-4 | 69-6 | 59-6 | 52-1 | 46-4 | 37-3 | 33-4 | 26-0 | 18-11 | 13-0 | 9-6 | 6-6 | 4-9 |
| 3" 75 mm. ... | 166-6 | 125-0 | 100-0 | 83-4 | 71-5 | 62-6 | 55-7 | 44-7 | 40-0 | 31-3 | 22-9 | 15-7½ | 11-5 | 7-10 | 5-9 |
| 3½" 87.5 mm. ... | 194-6 | 146-0 | 116-8 | 97-3 | 83-4 | 73-0 | 64-10 | 52-0 | 46-8 | 36-6 | 26-6 | 18-3 | 13-3 | 9-1½ | 6-7½ |
| 4" 100 mm. ... | 222-0 | 166-9 | 133-4 | 111-0 | 95-3 | 83-5 | 74-2 | 59-6 | 53-4 | 41-9 | 30-4 | 20-10½ | 15-2 | 10-5 | 7-7 |
| 4½" 112.5 mm. ... | 187-6 | 150-0 | 125-0 | 107-2 | 93-10 | 83-5 | 74-0 | 60-0 | 60-0 | 46-11 | 34-2 | 23-6 | 17-1 | 11-9 | 8-7 |
| 5" 125 mm. ... | 208-6 | 166-8 | 139-0 | 119-1 | 104-4 | 92-8 | 74-6 | 66-8 | 66-8 | 52-2 | 37-11 | 26-1 | 19-0 | 13-0 | 9-6 |
| 5½" 137.5 mm. ... | 229-3 | 183-4 | 152-9 | 131-0 | 114-7 | 101-10 | 81-10 | 73-6 | 73-6 | 57-4 | 41-9 | 28-8 | 20-11 | 14-4 | 10-6 |
| 6" 150 mm. ... | 250-0 | 200-0 | 166-9 | 142-11 | 125-0 | 111-2 | 89-3 | 80-0 | 80-0 | 62-6 | 45-7 | 31-2 | 22-10 | 15-7½ | 11-5 |
| 7" 175 mm. ... | 233-4 | 194-3 | 166-9 | 146-0 | 129-9 | 119-0 | 104-3 | 93-6 | 93-6 | 73-0 | 53-0 | 36-6 | 26-6 | 18-3 | 13-3 |
| 8" 200 mm. ... | 266-8 | 222-0 | 190-6 | 166-9 | 148-3 | 119-0 | 106-8 | 83-5 | 83-5 | 60-6 | 41-9 | 30-3 | 20-11 | 15-2 | 11-5 |
| 10" 250 mm. ... | 333-4 | 277-9 | 238-3 | 208-6 | 185-3 | 149-0 | 133-4 | 104-3 | 104-3 | 75-8 | 52-7½ | 37-10 | 26-4 | 18-11 | 13-3 |
| 12" 300 mm. ... | 400-0 | 333-3 | 285-9 | 250-0 | 222-3 | 178-6 | 160-0 | 125-0 | 125-0 | 90-10 | 62-6 | 45-5 | 31-3 | 22-9 | 15-2 |
| 15" 375 mm. ... | 416-9 | 357-0 | 312-6 | 278-0 | 223-0 | 200-0 | 156-3 | 113-6 | 113-6 | 78-1½ | 56-9 | 39-1 | 28-4 | 18-1 | 13-3 |
| 18" 450 mm. ... | 500-0 | 428-9 | 375-0 | 333-6 | 268-0 | 240-0 | 187-6 | 136-6 | 136-6 | 93-9 | 68-3 | 46-11 | 34-2 | 24-2 | 18-1 |
| 20" 500 mm. ... | 555-6 | 476-3 | 417-0 | 371-0 | 298-0 | 266-6 | 208-6 | 151-6 | 151-6 | 104-3 | 75-9 | 52-2 | 37-10 | 27-10 | 19-1 |

i.e., at $f/6$ and allowance has to be made for this in working out exposure times.

Effective f /numbers when a lens is used with supplementary lenses are discussed on pages 52 and 190.

There is no need to use this correction to the f /number in working out depths of field, as it is not applicable there. The f /number engraved on the lens mount is accurate for depth of field calculations. The relevant quantity is the diameter of the beam of light as it is expressed by the f /number on the mount.

The word *transmission* was used freely in earlier editions in this section. It is now restricted to the specialised meaning on p. 288.

Calculation of Depth of Field

The points A , B , and C , D , are taken as limiting the areas on the principal planes at which light rays may aim, when they come from points on the axis and go into the lens, and from which they aim as they come to a focus. This is shown on p. 61. P is a point on the lens axis whose image is the point Q . The extreme rays that the lens transmits are shown by the rays joining P with A and B , and Q with C and D . The plate or film is at right angles to the lens axis through the point Q .

The point R has its image at S . The extreme rays from R that go through the lens are shown on p. 61. They form a disc of the correct size on the plate at Q , according to the formula given on page 60, i.e., .004 inch for a 4 inch lens.

In the same way the point T has its image at W , and the extreme rays again are shown. And again the disc is of the correct size according to the formula of page 60.

The points R and T set the limits within which objects are sufficiently sharply defined. They measure off the depth of field of the lens, when the lens is focused on the point P .

To calculate the positions of these limits of the depth of field, in view of the principles already laid down in this section, is purely a question of manipulating mathematical symbols. And it results from this manipulation that the limits of the depth of focus are best calculated in two stages.

*Hyperfocal Distance*¹: The first stage is to calculate the "hyperfocal distance" of the lens, call it H .

The formula for H (measured from the lens node) is

$$H = f + \frac{1000 f}{N} \text{ Inches,}$$

where f is the focal length of the lens in inches, and N is the f /number of the lens. For most practical purposes this may be simplified to—

$$H = \frac{1000f}{N} \text{ inches.}$$

Thus for a 2 inch f 3 lens, $H = (2 \times 1000) \div 3 = .667$ inches.

The hyperfocal distance has this property—if a lens is focused on the hyperfocal distance then all points are within the range covered by the depth of field, from infinity down to half the hyperfocal distance. In the above case, if the lens is focused on 55 feet 7 inches, then the depth of field means that all objects are reproduced sufficiently sharply from infinity down to half of 55 feet 7 ins. i.e., 27 feet 9½ ins.

The hyperfocal distance is not something definite for a lens alone. It is definite only for a lens at a particular "aperture," and changes as the lens is stopped down. The more the lens aperture is reduced the shorter is the hyperfocal distance. It must be worked out separately for each lens aperture.

Nearest and Farthest Limits of Depth : The second stage is to calculate the depth of field when the lens is focused on a point at a distance u from the forward nodal point. Actually it is sufficiently close to measure u from the front of the lens, and in what follows it will be assumed that u is the distance of the point from the front of the lens.

The formulæ for the nearest and farthest limits of the depth of field are—

$$\text{Nearest limit} = \frac{fu(f + CN)}{f^2 + uCN}$$

$$\text{Farthest limit} = \frac{fu(f - CN)}{f^2 - uCN}$$

where u is the distance from the lens node to object, C the diameter of the disc of confusion, and N the f /number.

The following simplified formulæ may be used without serious loss of accuracy for most practical purposes—

$$\text{Nearest limit} = \frac{H \times u}{H + u}$$

$$\text{Farthest limit} = \frac{H \times u}{H - u}$$

When the denominator in any of the above formulæ for the farthest limit is zero or negative, the farthest limit is infinity.

For object distances less than 10 times the focal length the following formula is preferable—

$$\text{Total depth (far to near)} = \frac{2CN(M + 1)}{M^2}$$

where M is the scale of reproduction (object size to image size, this is less than unity when the image is smaller than the object).

This illustrates the fact that, for a given particular size of the disc of confusion, depth is only dependent on magnification between object and image and on relative aperture. This fact is not immediately apparent from the tables on pages 78–93 since these assume a variable size of disc equal to $f/1000$.

As an example of the use of these formulæ suppose that with the lens in use the hyperfocal distance is 667 inches, as in the case described above, and that the lens is focused on a distance of 15 feet, i.e., 180 inches. The formulæ then gives for the depth of field limits

$$\text{Nearest limit} = \frac{667 \times 180}{667 + 180} = \frac{667 \times 180}{847} = 141.5 \text{ inches to the nearest half inch.}$$

$$\text{Farthest limit} = \frac{667 \times 180}{667 - 180} = \frac{667 \times 180}{487} = 244.5 \text{ inches to the nearest half inch.}$$

To get a complete depth of field chart for the lens these two stages have to be gone through for every lens stop and for every focusing distance. Tables for a number of popular lenses are given on pages 64, 78–93.

There is one point to mention : in some cases a lens when set for infinity actually focuses on the hyperfocal distance of the largest aperture of the lens. While this results in a gain in the depth of field when the lens is focused on this distance—the depth of field now extends from half the hyperfocal distance to infinity whereas when the lens is focused on infinity the depth of field extends only from the hyperfocal distance to infinity—something in sharpness of definition is lost when it is required to photograph an object beyond the hyperfocal distance. It will be assumed that the lens is focused on infinity when it is set for infinity, throughout this book.

III.—HYPERFOCAL DISTANCES FOR A 2 INCH LENS

| <i>Aperture.</i> | <i>Hyperfocal Distance H.</i> |
|------------------|-------------------------------|
| <i>f</i> 2 | 1000 inches |
| <i>f</i> 2.8 | 700 " |
| <i>f</i> 4 | 500 " |
| <i>f</i> 5.6 | 350 " |
| <i>f</i> 8 | 250 " |
| <i>f</i> 11 | 175 " |

Table III gives the hyperfocal distances for a 2 inch lens at various apertures ; Table IV gives the nearest and farthest limits of depth of field for these distances.

IV.—LIMITS OF DEPTH OF FIELD

| <i>Focused Distance.</i> | <i>Limiting Distances of Depth of Field.</i> | | | | | |
|--------------------------|----------------------------------------------|-------------------------------|------------------------------|-------------------------------|-----------------------------|-----------------------------|
| | <i>H = 1000"</i> | <i>H = 700"</i> | <i>H = 500"</i> | <i>H = 350"</i> | <i>H = 250"</i> | <i>H = 175"</i> |
| 4ft. | 3ft. 9½ins. 4ft. 2½ins. | 3ft. 9 ins. 4ft. 3½ins. | 3ft. 8ins. 4ft. 5ins. | 3ft. 6 ins. 4ft. 7½ins. | 3ft. 4½ins. 4ft. 11½ins. | 3ft. 2 ins. 5ft. 6 ins. |
| 7ft. | 6ft. 5½ins. 7ft. 7½ins. | 6ft. 3 ins. 7ft. 11½ins. | 6ft. 0ins. 8ft. 5ins. | 5ft. 7½ins. 9ft. 2½ins. | 5ft. 3 ins. 10ft. 8 ins. | 4ft. 9 ins. 13ft. 5½ins. |
| 10ft. | 8ft. 11ins. 11ft. 4ins. | 8ft. 6½ins. 12ft. 1 in. | 8ft. 1in. 13ft. 2ins. | 7ft. 5½ins. 15ft. 2½ins. | 6ft. 9 ins. 19ft. 3 ins. | 5ft. 11ins. 31ft. 10ins. |
| 15ft. | 12ft. 8½ins. 18ft. 3½ins. | 11ft. 11 ins. 20ft. 2 ins. | 11ft. 0ins. 23ft. 5ins. | 9ft. 11 ins. 30ft. 10½ins. | 8ft. 8½ins. 53ft. 7 ins. | 7ft. 4½ins. Infinity. |
| 25ft. | 19ft. 3 ins. 35ft. 9 ins. | 17ft. 6 ins. 43ft. 9 ins. | 15ft. 7½ins. 62ft. 6 ins. | 13ft. 5½ins. 175ft. 0 ins. | 11ft. 4½ins. Infinity. | 9ft. 2½ins. Infinity. |
| Infinity. | 83ft. 4 ins. Infinity. | 58ft. 4 ins. Infinity. | 41ft. 8 ins. Infinity. | 29ft. 2 ins. Infinity. | 20ft. 10ins. Infinity. | 14ft. 7 ins. Infinity. |

Depth of Focus

There is one subject closely allied to depth of field, namely the question of how far the plate or film can move

from the position of exact focus, and yet reproduce a sufficiently good quality image of the object on which the lens is supposed to focus. This is the *depth of focus*.

A formula can be worked out on the lines used in laying down the principles governing depth of field, and one that is accurate to within about 15 per cent is as follows—

$$\text{the permissible shift of the plate} = f^2 \div H$$

where f is the equivalent focus of the lens, and H the hyper-focal distance.

Alternatively the permissible shift can be obtained from the formula—

$$\text{Permissible shift} = \frac{Cv (f/\text{number})}{f}$$

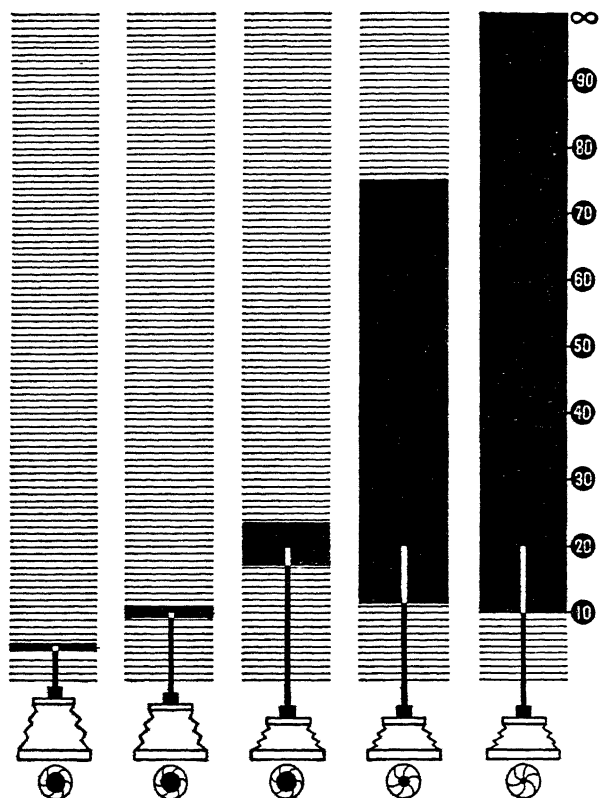
where C is the diameter of the disc of confusion, v the conjugate distance lens to image. For very distant objects v is practically equal to f so that permissible shift is $C (f/\text{number})$.

Thus, in the case worked out above, where $h = 667$ inches and $f = 2$ inches, the permissible displacement (i.e., depth of focus) is $2^2 \div 667 = 4 \div 667 = .006$ inch.

It is worth noting that the formulæ just given provide an indication of how closely a lens must be set on its nominal focusing position so that the subject thought to be in focus will provide an image of acceptable quality.

An Alternative Criterion of Sharpness

And finally, although the question of depth of field has been treated from the point of view of arriving at the diameter of the disc on the plate, when seen at the least distance of clear vision, and enlarged up to give the correct perspective at this distance, there is another way of looking at the matter. *In this case no attention is paid to enlarging but attention is concentrated on the actual size of the disc on the plate.* This results in attributing to the lens a spectacular standard of performance. For instance with the 2 inch focus lens commonly used in miniature work, the diameter of the disc on the plate, or circle of confusion as it is often called, is

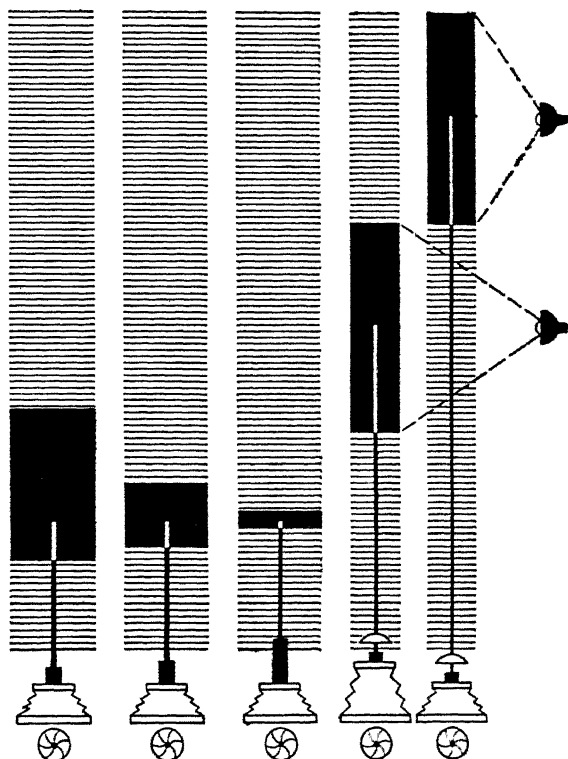


The extent of the depth of field obtainable grows with the distance focused at and with the f number used, and diminishes with increasing focal length.

The first three drawings show the use of the same lens at the same stop, with the point focused at moved further and further away from the camera. The heavily shaded areas indicate the growing depth of field; it grows from left to right.

The last two drawings right show the same lens still in use, focused at the same point as the drawing in the centre, but stopped down gradually, say, to 9 and 12.5, assuming that the original stop used (in the first three drawings) was 3.5. The extensive growth of the depth of field is obvious.

DEPTH OF FIELD IN PRACTICE.



Using the same focusing distance as in the *last three* drawings and the same stop as in the *very last* (p. 70), while working with lenses of a focal length fifty, one hundred and two hundred per cent longer than the lens exemplified in the *first five* drawings, the depth of field will rapidly diminish as shown in the *first three* drawings of this page.

Right (two diagrams) : By illuminating the region of the depth of field with a particular lens setting and photographing it, then changing the lens focus with a supplementary lens so that the new region of depth of field joins on to the former, illuminating and photographing this, the depth of field can be increased without the need for stopping down the lens. Automatic application of this method for cine-work is the subject of a recent American patent (p. 75).

DEPTH OF FIELD IN PRACTICE.

taken to be .002 inch. The limit of sharp definition is taken to be reached when the disc of confusion reaches one five-hundredth of an inch. This, of course, is just the diameter of the disc demanded from the treatment given earlier. When a diameter of .002 inch is required with a lens of 4 inches the standard is higher than that demanded earlier.

The special use of concentrating attention on the actual size of the disc is when dealing with short focus lenses, when the diameter of the disc becomes comparable with the size of the grain in the negative. The actual size of the grain depends of course on the negative material and no general ruling can be given. The best thing is to work out the depth of field in a general formula, calling the diameter of the disc of confusion C when measured in thousandths of an inch.

The method of working out the depth of field is exactly the same as before except that a new hyperfocal distance H (new) is worked out and used where H was used before. The formula for H (new) is

$$H \text{ (new)} = \frac{1000 \times f^2}{C \times N} \text{ inches,}$$

where f is the equivalent focal length of the lens, N is the f /number of the lens stop used, and C is the number of thousandths of an inch in the diameter of the disc of confusion on the plate.

For instance with a 15 mm. $f2.5$ lens such as is sometimes mounted on 16 mm. cameras, assuming that the graininess of the film means that it is of no use considering that the image on the negative is smaller than .001 inch, i.e., fixing the diameter of the disc of confusion at .001 inch, then $c = 1$ and the formula for H (new) is

$$H \text{ (new)} = \frac{1000 \times \left(\frac{15.0}{25.4}\right)^2}{1 \times 2.5} = 140 \text{ inches to the nearest inch.}$$

The factor $15 \div 25.4$ is needed to measure the equivalent focal length in inches.

Therefore with this standard of definition which has been assumed to be dictated by the graininess of the film, all objects are equally sharp from 70 inches to infinity, and as this is a useful working range for the camera it is feasible to fit a lens straight away to the camera, without a focusing mount.

Once the H (new) is calculated everything goes ahead as before.

For miniature work there is rarely, if ever, any need to take a disc of confusion of less than .002 inch in diameter, or at the most .0015 inch. For 35 and 16 mm. cine work the same standard will suffice with an upper limit of .001 inch. For $9\frac{1}{2}$ mm. film it is sufficient to take a diameter of .001 inch. Excepting these special cases the calculation of a depth of field chart is best carried out using the earlier form, with H not H (new). And even for miniature work there is a lot to be said for using the earlier procedure rather than basing results on a fixed size of .002 inch for the disc of confusion; although it is largely a matter of individual taste.

Some still further aspects of depth of field are dealt with on pages 129-133 and 260-264.

Comparative Depths of Field

The question often arises: A scene is to be photographed in such a way that the depth of field is to be a maximum. Is it better to use a long focus lens and make a contact print, or to use a short focus lens and make an enlargement?

The answer is in favour of the short focus lens.

Take a concrete example. The given scene is photographed with an 8 inch lens and with a 2 inch lens, both working at the same aperture, say $f/4$, and both at 10 feet from some feature of the scene to be recorded. Since they are both working at the same f /number the same exposure is needed in each case. The negative obtained with the 8 inch lens is used to make a contact print. A four-fold enlargement is given to the negative produced by the 2 inch lens. Which will have the greatest region of the scene sharp?

The hyperfocal distance H (1) for the 8 inch lens is $(8 \times 1000) \div 4 = 2000$ inches" (cf. page 66).

The nearest distance in focus when the lens is focused on 10 feet, i.e., 120 inches, is $\frac{2000 \times 120}{2000 + 120} = 113.2$ inches.

The farthest distance is $2000 \times 120 \div (2000 - 120)$, i.e., 127.7 inches.

The hyperfocal distance for the 2 inch lens is 500 inches, and in the same way the nearest distance is 96.8 inches, and the farthest distance 157.9 inches.

The range with the 8 inch lens is 14.5 inches, and with the 2 inch lens 61.1 inches, i.e., just over 4 times as great.

A rough rule is that the range at the same f /number is doubled if the focal length is halved, and so on.

The condition that the contact print and the enlargement should have the same standard of definition is taken care of by the method of calculating the hyperfocal distance, as dealt with on page 66.

Production of Depth by Lens Movement

A topic which is related on the one hand to the possibility of increasing the depth of field of the lens, and on the other hand to the production of a soft focus effect (page 178) which is demanded by some classes of photography, is the effect of moving the lens or adding a supplementary lens while the exposure is being made.

Neglecting all lens aberrations, as has been done consistently throughout this chapter, in any setting of the lens points of light in a certain plane in front of the lens give bright point images on the sensitive plate or film. Points of light in other planes give discs of light on the film or plate. These are not so bright as the exactly focused points of light, since the light is spread over the area of the disc instead of being concentrated at its centre. Up to a certain limiting size it is not easy, except on close inspection, to see that the discs are not points, and within these limits subjects to be photographed are reasonably well defined. Outside these limits the subject is out of focus, and each point of light is reproduced as a more or less tenuous disc.

Now suppose that the lens position is shifted so that a point of light which previously gave a disc of light is brought into focus on the plate or film. What is then recorded on the sensitised surface is a bright point of light together with a fainter disc surrounding it. This is apprehended by the eye as being more in the nature of a point than the out of focus

disc of light, and the definition seems sharper, as far as those elements of the picture are concerned which were previously out of focus. Those parts which were sharply in focus before are now softened somewhat, as they are out of focus, while other elements are sharply focused.

The net result is that the definition is somewhat softened overall, but the definition is more even throughout the picture.

Alternatively the focus of the lens can be changed to varying values with the aid of supplementary lenses, and a series of exposures made.

This idea of changing the focus of a lens is not new, but it is difficult to carry out unless a comparatively long exposure is being made, say of an indoor scene. An ingenious patent of *Bausch and Lomb* describes a lens in which the focal length is changed by the movement of one of the component glasses in a lens at the rate of more than 20,000 times a second. This lens is meant for work in cine studios.

Another American patent deals with quite an interesting modification of the method with the aim of obtaining depth of field without overall softening of the definition. In essentials it means that *the lens is focused on part of the scene, and only that part is illuminated which falls within the depth of field of the lens*, so that its image is in sufficiently sharp focus on the film. The lens focus is then changed or a supplementary lens used so that the part of the scene now in focus begins where the earlier part finished, and this is illuminated and photographed. The lighting and lens change are synchronised so that the operation is automatic.

To make it clearer how this last method works consider a concrete example : with a 2 inch $f\ 2.5$ lens the hyperfocal distance is 800 inches. If it is focused on 140 inches the range inside the depth of field extends from 120 inches to 185 inches : this part of the scene is illuminated and photographed. A supplementary lens is then put in position so that the lens focuses on 240 inches. The range now photographed extends from 185 inches to 343 inches. Finally the lens is focused by means of a supplementary lens on a distance of 600 inches, and the range photographed extends from 343 inches to 200 feet. In this way the region from 10 feet to 200 feet is covered sharply. In normal circumstances this would need a lens stopped down to $f\ 9$, and so passing only one-thirteenth of the light passed by the $f\ 2.5$ lens.

Depth of Field Tables

Depth of field tables are given in the following pages for a number of popular focal lengths, lens apertures, and focusing distances. These are calculated on the basis of a circle of confusion of .001" per inch of focal length, i.e. with a circle of .005" diameter for a 5" lens.

The range of availability of these tables can be extended by bearing in mind the following facts.

Suppose in the first place that the lens aperture is not among those listed. This is most likely to happen in the region of $f/3$ and faster. At small apertures and high f numbers these latter are fairly well standardised, except for an occasional variation such as $f/7.7$ in place of $f/8$ or $f/33$ in place of $f/32$, deviations which are quite negligible. But at the other end of the scale there are lenses listed of apertures $f/1.3$, $f/1.4$, $f/1.9$, $f/2.7$, $f/2.8$, etc. Consider the specific case of a 4" $f/2.7$ lens. The lenses given in the tables are $f/2.5$ and $f/3$. If the depth of field for a 4" $f/2.5$ lens is taken this corresponds to the use of a circle of confusion not .004" diameter for a 4" lens, but to a diameter of $.004" \times (2.5/2.7)$ or a difference in diameter of $7\frac{1}{2}\%$. On the other hand if the depth of field listed for a 4" $f/3$ lens is taken as being applicable to a 4" $f/2.7$ lens, this amounts to assuming a circle of confusion of $.004" \times (3.0/2.7)$ or a difference of 11%. Taking the $f/2.5$ figures as being applicable to an $f/2.7$ lens means that a standard of definition higher by $7\frac{1}{2}\%$ is adopted. Taking the $f/3$ figures means that the definition is 11% below the standard value of .001" per inch of focal length.

Since the fall off in definition is taken to be uniform from the position of sharp focus, and not a slow fall off up to the limits of the depth of field followed by a catastrophic degeneration, there is a considerable arbitrary element in fixing the limits of the depth of field. They have been worked out on the assumption of a disc of confusion of .001" for each inch of focal length, and serve very well as a guide in fixing the region where the definition is up to standard. But it is to be remembered that they are a guide only, and that limits worked out with a disc of confusion 10-15% larger or smaller would not yield very different pictorial results.

For all practical purposes a deviation of 10%-15% in the diameter of the disc of confusion is negligible. Hence the figures for $f/2.5$ or $f/3$ are applicable to an $f/2.7$, or $f/2.8$ lens, and the $f/3$ figures to an $f/2.9$ or $f/3.1$ lens. The same thing holds for other unlisted apertures.

In the next place the lens focus may not be listed. Suppose for example that the lens to be used is a $4\frac{1}{4}" f/4.5$. If the figures for a $4\frac{1}{2}" f/4.5$ are assumed to be applicable this amounts to taking a disc of confusion smaller than the standard by $(4\frac{1}{4}"/4\frac{1}{2}")$ i.e. by 6%. Taking the 4" $f/4.5$ figures as applicable to a $4\frac{1}{4}" f/4.5$ means assuming a disc of confusion greater than the standard by $(4\frac{1}{4}"/4\frac{1}{2}")$ i.e. by 6%. Again these discrepancies are negligible in practical work, and the same holds for other unlisted foci which can be dealt with in this way.

When both focus and aperture are unlisted the situation is not essentially more complicated. Suppose for instance that the lens is a $3\frac{1}{4}" f/2.8$. Taking the $f/3$ figures means assuming a disc that is larger by $(3/2.8)$ i.e. by 7%. Taking the $3\frac{1}{2}"$ figures means assuming a disc smaller by $(3\frac{1}{4}"/3\frac{1}{2}')$ i.e. by 7%. Hence the figures for a $3\frac{1}{2}" f/3$ are applicable to a

$3\frac{1}{2}" f 2.8$ with no appreciable error. The $3"$ figures mean a disc larger by $(3.25/3)$ i.e. by 8% , and the $f 2.5$ figures a disc smaller by $(2.5/2.8)$ i.e. by 11% , and hence the use of the $3" f 2.5$ figures for a $3\frac{1}{2}" f 2.8$ lens means that a disc of confusion is adopted that is smaller than the standard by 3% , a negligible difference. *The rule in these cases is that both the f numbers and the focus must move together in the same direction, e.g. $3\frac{1}{2}"$ and $f 2.8$ to $3\frac{1}{2}"$ and $f 3$, or $3\frac{1}{2}"$ and $f 2.8$ to $3"$ and $f 2.5$.*

The tables have been calculated on the basis of a circle of confusion of $.001"$ for each inch of focal length as this is probably the best value for all round use. Other values that are used are diameters two-thirds and one-half of this diameter for the disc of confusion. These can be dealt with by taking the f number of the lens and multiplying it by two-thirds and a half respectively to get an equivalent f number, and then dealing with the lens solely on the basis of this equivalent f number. For instance suppose that a lens in use is a $2" f 3$ and that the depth of field is to be calculated on the basis of a disc half the standard diameter, i.e. $.0005"$ per inch of focal length, then the depth of field limits are those given for a lens of $f 1.5$ aperture and $2"$ focus. Alternatively the same circumstances can be dealt with by multiplying the focal length of the lens by $1\frac{1}{2}$ and 2 respectively, keeping the f number the same. Thus in the example quoted the limits of the depth of field are those listed for a $4" f 3$ lens.

An instance of the case where this last type of procedure is required is that of a telephoto lens. Suppose that we have a $2 \times 6" f 4.5$ telephoto, then the limits of the depth of field are found in the $6" f 2.25$ tables, i.e. sufficiently closely in the $6" f 2.5$ or $6" f 2$ tables. A similar procedure has to be followed for other foci and apertures.

The case where the focusing distance is not listed is not quite so easy to handle. Suppose that a $4" f 4.5$ lens is focused on 22 feet. The limits for a focusing distance of 20 feet are 15-9 and 27-4, for a distance of 25 feet 18-8 and 37-9. Hence for 20 feet the range inside the focus is 4-3 and outside the focus 7-4, while for 25 feet the range is 6-4 inside and 12-9 outside. Hence for a focusing distance of 22 feet what can be said is that the range inside the focus is between 4-3 and 6-4 and is nearer to the 4-3 position, say 5 feet, giving a near limit of 17 feet. Similarly we can set a far limit of about 31-6. An actual calculation gives the values 17-0, and 31-3. Estimates of this type give useful indications when the focusing distances are not listed.

In a minority of cases it may be advisable to recalculate the depth of field table for a particular set of apertures and focusing distances and for a particular lens focus, but in the majority of cases the tables given, used as explained above, will suffice.

Depth of field values may also be obtained by the use of a calculating device, one form of this being the scale that is an integral part of the focusing movement of a lens on a miniature camera. To cover a range of focal lengths, and to serve as a useful adjunct to cameras not fitted with such depth of field indicators, the *Focal Focusing Chart* has been prepared by the author and publishers of this book. The results of calculations on topics discussed in the present chapters have also been tabulated in it, for easy reference. Depth of field tables give more accurate results, but in many instances a calculating device, such as the chart, is more handy to use.

V.—DEPTH OF FIELD FOR LENSES OF 1 INCH (25 mm.) FOCAL LENGTH

| | |
|------|--------------------------------------------------------------------------|
| f1.5 | 1-11 2-4 2-10 3-8 4-7 5-5 6-2 7-0 7-9 8-5 9-10 11-10 14-9 19-6 26-4 55-6 |
| | 2-1 2-7 3-2 4-3 5-6 6-8 7-0 8-9 10-9 12-2 15-4 20-7 31-3 65-4 605-0 |
| f2.0 | 1-10 2-4 2-9 3-7 4-5 5-3 6-0 6-8 7-5 8-0 9-4 11-0 13-6 17-6 22-9 41-8 |
| | 2-1 2-8 3-3 4-5 5-8 7-0 8-5 9-11 11-6 13-2 16-10 23-5 38-5 62-6 50-0 |
| f2.5 | 1-10 2-3 2-9 3-6 4-4 5-1 5-9 6-5 7-1 7-8 8-10 10-4 12-6 15-9 20-0 33-4 |
| | 2-1 2-7 3-2 4-4 5-5 6-2 7-7 8-8 9-10 12-2 15-4 20-7 31-3 65-4 605-0 |
| f3.0 | 2-1 2-8 3-3 4-6 5-10 7-3 8-10 10-6 12-4 14-3 18-9 27-3 50-0 300-0 00-0 |
| | 1-10 2-3 2-8 3-6 4-2 4-11 5-7 6-2 6-9 7-4 8-4 9-9 11-7 14-5 17-10 27-9 |
| | 2-1 2-9 3-4 4-8 6-1 7-8 9-4 11-3 13-4 15-7 21-2 32-7 71-7 00-0 00-0 |
| f3.5 | 1-10 2-3 2-8 3-5 4-1 4-9 5-5 6-0 6-6 7-0 8-0 9-2 10-10 13-3 16-1 23-10 |
| | 2-1 2-7 3-2 4-4 5-5 6-2 7-7 8-8 9-10 12-2 15-4 20-7 31-3 65-4 605-0 |
| f4.0 | 1-9 2-2 2-7 3-4 4-0 4-8 5-2 5-9 6-3 6-9 7-7 8-8 10-2 12-3 14-8 20-10 |
| | 2-1 2-8 3-3 4-5 6-7 8-5 10-6 13-0 15-10 19-3 28-4 53-7 500-0 00-0 |
| f4.5 | 1-9 2-2 2-7 3-3 4-1 4-6 5-1 5-7 6-0 6-6 7-3 8-3 9-7 11-5 13-6 18-6 |
| | 2-1 2-8 3-3 4-5 6-7 8-5 10-6 13-0 15-10 19-3 28-4 53-7 500-0 00-0 |
| f5.6 | 1-9 2-1 2-5 3-1 3-8 4-3 4-9 5-2 5-7 5-11 6-7 7-5 8-6 9-10 11-4 14-8 |
| | 2-1 2-8 3-3 4-5 6-7 10-2 13-5 17-7 23-3 31-5 792-0 00-0 00-0 00-0 |
| f6.3 | 1-8 2-1 2-5 3-1 3-7 4-1 4-7 5-0 5-4 5-8 6-4 7-0 8-0 9-3 10-6 13-4 |
| | 2-1 2-8 3-3 4-5 6-7 10-2 13-5 17-7 23-3 31-5 792-0 00-0 00-0 00-0 |
| f8 | 1-8 2-0 2-4 2-10 3-4 3-9 4-2 4-6 4-10 5-1 5-7 6-2 6-10 7-9 8-7 10-5 |
| | 2-1 2-8 3-3 4-5 6-7 10-2 13-5 17-7 23-3 31-5 792-0 00-0 00-0 00-0 |
| f11 | 1-7 1-10 2-1 2-7 3-0 3-4 3-7 8-10 4-1 4-3 4-7 5-0 5-5 6-0 6-6 7-6 |
| | 2-1 2-8 3-3 4-5 6-7 10-2 13-5 17-7 23-3 31-5 792-0 00-0 00-0 00-0 |
| f16 | 1-5 1-10 2-3 2-9 3-0 3-2 3-3 3-5 3-7 3-10 4-1 4-5 4-8 5-3 |
| | 2-1 2-8 3-3 4-5 6-7 10-2 13-5 17-7 23-3 31-5 792-0 00-0 00-0 00-0 |
| f22 | 1-3 1-6 1-8 1-11 2-1 2-3 2-5 2-6 2-8 2-10 3-0 3-2 3-4 3-6 3-9 |
| | 2-1 2-8 3-3 4-5 6-7 10-2 13-5 17-7 23-3 31-5 792-0 00-0 00-0 00-0 |

VI.—DEPTH OF FIELD FOR LENSES OF 1½ INCH (28 mm.) FOCAL LENGTH

| | | | | | | | | | | | | | | | | |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|------|-------|-------|
| f 1.5 | 1-11½ | 2-4½ | 2-10½ | 3-9 | 4-7½ | 5-5½ | 6-3½ | 7-1 | 7-10½ | 8-7½ | 10-1 | 12-1 | 15-2 | 20-3 | 27-9 | 62-6 |
| | 2 | 2½ | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 20 | 30 | 50 | ∞ |
| 2-0½ | 2-7½ | 3-1½ | 4-3½ | 5-5½ | 6-7½ | 7-10½ | 8-2 | 9-6 | 10-6 | 11-11 | 14-10 | 19-9 | 29-5 | 57-9 | 250-0 | ∞ |
| f 2 | 1-11 | 2-4½ | 2-9½ | 3-8½ | 4-6½ | 5-3½ | 6-1 | 6-10 | 7-6½ | 8-3 | 9-6½ | 11-4 | 14-0 | 18-3 | 24-2 | 46-11 |
| | 2 | 2½ | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 20 | 30 | 50 | ∞ |
| 2-1 | 2-7½ | 3-2½ | 4-4½ | 5-7½ | 6-10½ | 8-2½ | 9-8 | 11-1½ | 12-8½ | 16-1½ | 22-1 | 34-11 | 83-6 | ∞ | ∞ | ∞ |
| f 2.5 | 1-10½ | 2-4½ | 2-9½ | 3-7½ | 4-5 | 5-2 | 5-11 | 6-7 | 7-3 | 7-10½ | 9-1 | 10-8 | 13-0 | 16-8 | 21-5 | 37-6 |
| | 2 | 2½ | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 20 | 30 | 50 | ∞ |
| 2-1½ | 2-8½ | 3-3½ | 4-5½ | 5-9½ | 7-1½ | 8-5½ | 10-2 | 11-10 | 13-7½ | 17-8 | 25-0 | 42-10 | 150-0 | ∞ | ∞ | ∞ |
| f 3.0 | 1-10½ | 2-3½ | 2-8½ | 3-6½ | 4-3½ | 5-0½ | 5-8½ | 6-4½ | 7-0 | 7-7 | 8-8 | 10-1½ | 12-2 | 15-4 | 19-9 | 31-3 |
| | 2 | 2½ | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 20 | 30 | 50 | ∞ |
| 2-1½ | 2-8½ | 3-3½ | 4-7 | 5-11½ | 7-5 | 9-0 | 10-9 | 12-7½ | 14-8½ | 19-6 | 28-10 | 55-6 | 750-0 | ∞ | ∞ | ∞ |
| f 3.5 | 1-10½ | 2-3½ | 2-8½ | 3-5½ | 4-2½ | 4-11 | 5-6½ | 6-2 | 6-9 | 7-3½ | 8-3½ | 9-7 | 11-5 | 14-2 | 17-5 | 26-9 |
| | 2 | 2½ | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 20 | 30 | 50 | ∞ |
| 2-1½ | 2-9½ | 3-4½ | 4-8½ | 6-2 | 7-9 | 9-6 | 11-5 | 13-7 | 16-0 | 21-9 | 34-2 | 79-2 | ∞ | ∞ | ∞ | ∞ |
| f 4 | 1-10½ | 2-3½ | 2-7½ | 3-5 | 4-1½ | 4-9½ | 5-4½ | 6-0 | 6-6 | 7-0 | 8-0 | 9-2 | 10-9 | 13-2 | 16-0 | 23-6 |
| | 2 | 2½ | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 20 | 30 | 50 | ∞ |
| 2-2½ | 2-9½ | 3-5½ | 4-10 | 6-4½ | 8-0 | 10-0 | 12-1½ | 14-7 | 17-5 | 24-6 | 41-6 | 134-6 | ∞ | ∞ | ∞ | ∞ |
| f 4.5 | 1-9½ | 2-2½ | 2-7½ | 3-4½ | 4-0½ | 4-8 | 5-3 | 5-9½ | 6-3½ | 6-9 | 7-7½ | 8-8½ | 10-2 | 12-4 | 14-8 | 20-10 |
| | 2 | 2½ | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 20 | 30 | 50 | ∞ |
| 2-2½ | 2-10 | 3-6 | 4-11½ | 6-7 | 8-5 | 10-6 | 13-0 | 15-10 | 19-2 | 28-4 | 53-6 | 500-0 | ∞ | ∞ | ∞ | ∞ |
| f 5.6 | 1-9½ | 2-2½ | 2-6½ | 3-2½ | 3-10½ | 4-5 | 4-11½ | 5-5 | 5-10 | 6-3 | 7-0 | 7-11 | 9-1½ | 10-9 | 12-6 | 16-9 |
| | 2 | 2½ | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 20 | 30 | 50 | ∞ |
| 2-3½ | 2-1½ | 3-7½ | 5-3 | 7-1½ | 9-4 | 12-0 | 15-4 | 19-6 | 24-10 | 42-4 | 143-6 | ∞ | ∞ | ∞ | ∞ | ∞ |
| f 6.3 | 1-9½ | 2-1½ | 2-6 | 3-2 | 3-9 | 4-3½ | 4-9½ | 5-2½ | 5-7½ | 6-0 | 6-10 | 7-6 | 8-7 | 10-0 | 11-6 | 15-0 |
| | 2 | 2½ | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 20 | 30 | 50 | ∞ |
| 2-3½ | 3-0 | 3-9 | 5-5½ | 6-0 | 10-0 | 13-1½ | 17-2 | 22-6 | 30-0 | 60-0 | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ |
| f 8 | 1-8½ | 2-0½ | 2-4½ | 2-11½ | 3-6 | 4-0 | 4-4½ | 4-9 | 5-1½ | 5-5 | 5-11½ | 6-7 | 7-5 | 8-5 | 9-6 | 11-9 |
| | 2 | 2½ | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 20 | 30 | 50 | ∞ |
| 2-5 | 3-2 | 4-0½ | 6-0½ | 8-8½ | 12-3 | 17-4 | 25-0 | 38-6 | 67-0 | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ |
| f 11 | 1-7½ | 1-11½ | 2-2½ | 2-8½ | 3-2 | 3-6 | 3-10 | 4-1½ | 4-4½ | 4-7 | 5-0 | 5-5 | 6-0 | 6-8 | 7-3 | 8-6 |
| | 2 | 2½ | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 20 | 30 | 50 | ∞ |
| 2-7½ | 3-6½ | 4-7½ | 7-6½ | 12-2 | 20-5 | 39-8 | 136-0 | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ |
| f 16 | 1-6 | 1-9 | 1-11½ | 2-4½ | 2-8½ | 3-2½ | 3-4½ | 3-6½ | 3-8½ | 3-11½ | 4-2½ | 4-6½ | 4-11 | 5-3 | 5-10½ | 5-10½ |
| | 2 | 2½ | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 20 | 30 | 50 | ∞ |
| 3-0½ | 4-1 | 6-1½ | 12-6 | 33-6 | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ |
| f 22 | 1-4½ | 1-7 | 1-9 | 2-0½ | 2-3½ | 2-5½ | 2-9½ | 2-10½ | 3-0 | 3-1½ | 3-3½ | 3-6 | 3-8½ | 3-11 | 4-3 | 4-3 |
| | 2 | 2½ | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 20 | 30 | 50 | ∞ |
| 3-9½ | 6-1 | 10-2½ | 68-0 | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ |

VII.—DEPTH OF FIELD FOR LENSES OF 1½ INCH (35 mm.) FOCAL LENGTH

| | | | | | | | | | | | | | | | | |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|--------|-------|-------|--------|-------|-------|-------|-------|
| f 1.5 | 1-11½ | 2-5 | 2-10½ | 3-9½ | 4-8½ | 5-6½ | 6-5 | 7-3 | 8-0½ | 8-10 | 10-4½ | 12-6½ | 15-10 | 21-6 | 30-3 | 76-6 |
| | 2-0½ | 2½ | 3 | 3-1½ | 4-2½ | 5-4½ | 6-6 | 7-8½ | 8-11½ | 10-2½ | 11-6 | 14-3 | 18-8 | 27-1 | 49-5 | 144-4 |
| f 2 | 1-11½ | 2-4½ | 2-10½ | 3-9 | 4-7½ | 5-5½ | 6-3 | 7-0 | 7-9½ | 8-6 | 9-11 | 11-10½ | 14-10 | 19-8 | 26-8 | 57-4 |
| | 2-0½ | 2½ | 3 | 3-2 | 4-3½ | 5-5½ | 6-8½ | 7-11½ | 8-10-8 | 12-1½ | 15-2 | 20-3 | 30-9 | 63-0 | 390-0 | ∞ |
| f 2.5 | 1-11 | 2-4½ | 2-9½ | 3-8 | 4-6 | 5-3½ | 6-1 | 6-9½ | 7-6 | 8-2½ | 9-6 | 11-3 | 14-0 | 18-2 | 24-0 | 45-10 |
| | 2-1½ | 2-7½ | 3-2½ | 4-4½ | 5-7½ | 6-11 | 8-3 | 9-8 | 11-2 | 12-9 | 16-3 | 22-3 | 35-6 | 87-0 | ∞ | ∞ |
| f 3 | 1-10½ | 2-4½ | 2-9½ | 3-7½ | 4-5 | 5-2½ | 5-11 | 6-7½ | 7-3½ | 7-11 | 9-1½ | 10-9 | 13-1 | 16-9 | 21-7 | 38-3 |
| | 2-1½ | 2-8½ | 3-3 | 4-5½ | 5-9 | 7-1½ | 8-7 | 10-1½ | 11-9 | 13-6 | 17-9 | 24-8 | 42-0 | 140-0 | ∞ | ∞ |
| f 3.5 | 1-10½ | 2-3½ | 2-9 | 3-6½ | 4-4 | 5-1 | 5-9½ | 6-5½ | 7-0½ | 7-8 | 8-9½ | 10-3½ | 12-5 | 15-8 | 19-10 | 32-9 |
| | 2-1½ | 2-8½ | 3-3½ | 4-6½ | 5-10½ | 7-4 | 8-11 | 10-7 | 12-5 | 14-4 | 18-11 | 27-8 | 51-3 | 357-0 | ∞ | ∞ |
| f 4 | 1-10½ | 2-3½ | 2-8½ | 3-6 | 4-3 | 4-11½ | 5-7½ | 6-3 | 6-10 | 7-5 | 8-5½ | 9-10 | 11-9 | 14-8 | 18-2 | 28-8 |
| | 2-1½ | 2-8½ | 3-4½ | 4-7½ | 6-0½ | 7-7 | 9-3 | 11-1 | 13-1 | 15-4 | 20-8 | 31-5 | 66-3 | ∞ | ∞ | ∞ |
| f 4.5 | 1-10½ | 2-3½ | 2-8½ | 3-5½ | 4-2 | 4-10½ | 5-6 | 6-1 | 6-8 | 7-2 | 8-2 | 9-5 | 11-3 | 13-9 | 16-11 | 25-6 |
| | 2-2 | 2-9½ | 3-4½ | 4-9 | 6-2½ | 7-10 | 9-8 | 11-8 | 13-11 | 16-5 | 22-8 | 36-6 | 92-9 | ∞ | ∞ | ∞ |
| f 5.6 | 1-9½ | 2-2½ | 2-7½ | 3-4½ | 4-0½ | 4-7½ | 5-2 | 5-9 | 6-3 | 6-8½ | 7-7 | 8-8 | 10-2 | 12-2 | 14-6 | 20-6 |
| | 2-2½ | 2-10½ | 3-6½ | 4-11½ | 6-7½ | 8-6 | 10-7½ | 13-1 | 16-0 | 19-6 | 28-11 | 56-0 | 820-0 | ∞ | ∞ | ∞ |
| f 6.3 | 1-9½ | 2-2½ | 2-7 | 3-3½ | 4-1 | 4-6½ | 5-0½ | 5-7 | 6-0½ | 6-5½ | 7-2½ | 8-3 | 9-7 | 11-4 | 13-5 | 18-4 |
| | 2-2½ | 2-10½ | 3-7 | 5-1½ | 6-10½ | 8-11 | 11-4 | 14-2 | 17-8 | 22-0 | 34-9 | 82-6 | ∞ | ∞ | ∞ | ∞ |
| f 8 | 1-9 | 2-1½ | 2-5½ | 3-1½ | 3-8½ | 4-3 | 4-8½ | 5-1½ | 5-6½ | 5-10½ | 6-6 | 7-4 | 8-4 | 9-9 | 11-2 | 14-4 |
| | 2-3½ | 3-0½ | 3-9½ | 5-6½ | 7-8 | 10-4 | 13-8 | 18-1 | 24-2 | 33-0 | 73-9 | ∞ | ∞ | ∞ | ∞ | ∞ |
| f 11 | 1-8 | 2-0½ | 2-4 | 2-10½ | 3-4½ | 3-9½ | 4-2½ | 4-6½ | 4-10 | 5-1 | 5-7 | 6-2 | 6-10 | 7-9 | 8-7 | 10-5 |
| | 2-5½ | 3-3½ | 4-2½ | 6-6 | 9-7 | 14-2 | 21-4 | 34-6 | 66-3 | 250-0 | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ |
| f 16 | 1-6½ | 2-1½ | 2-1½ | 2-7 | 2-11½ | 3-3 | 3-6½ | 3-9½ | 4-0 | 4-2 | 4-6 | 4-10 | 5-3 | 5-9 | 6-3 | 7-2 |
| | 2-9½ | 3-10 | 5-2 | 9-0 | 16-6 | 36-10 | 301-0 | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ |
| f 22 | 1-5½ | 2-1½ | 1-11 | 2-3 | 2-7 | 2-9½ | 3-0 | 3-2 | 3-4 | 3-5½ | 3-8 | 3-10½ | 4-2 | 4-5½ | 4-9 | 5-3 |
| | 3-2½ | 4-9½ | 7-0 | 16-10 | 105-0 | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ |

VIII.—DEPTH OF FIELD FOR LENSES OF 1 INCH (42.5 mm.) FOCAL LENGTH

| | | | | | | | | | | | | | | | | |
|------|------|------|------|------|------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| f1.5 | 1-11 | 2-5 | 2-10 | 3-10 | 4-9 | 5-7 | 6-6 | 7-4 | 8-2 | 9-0 | 10-7 | 12-10 | 16-4 | 22-6 | 32-2 | 90-4 |
| | 2 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 20 | 30 | 50 | ∞ |
| f2 | 2-0 | 2-6 | 3-1 | 4-2 | 5-3 | 6-5 | 7-7 | 8-9 | 10-0 | 11-3 | 13-10 | 18-0 | 25-8 | 45-0 | 111-8 | ∞ |
| | 1-1 | 2-5 | 2-10 | 3-9 | 4-8 | 5-6 | 6-4 | 7-2 | 7-11 | 8-8 | 10-2 | 12-5 | 15-5 | 20-10 | 28-10 | 67-9 |
| f2.5 | 2-0 | 2-7 | 3-1 | 4-3 | 5-4 | 6-7 | 7-9 | 9-1 | 10-4 | 11-9 | 14-7 | 19-3 | 28-5 | 53-10 | 191-0 | ∞ |
| | 1-1 | 2-4 | 2-10 | 3-8 | 4-7 | 5-5 | 6-2 | 7-0 | 7-8 | 8-5 | 9-10 | 11-9 | 14-7 | 19-4 | 24-0 | 54-3 |
| f3 | 2-1 | 2-7 | 3-2 | 4-3 | 5-6 | 6-9 | 8-0 | 9-4 | 10-9 | 12-3 | 15-5 | 20-9 | 31-8 | 67-3 | 650-0 | ∞ |
| | 1-1 | 2-4 | 2-9 | 3-8 | 4-6 | 5-3 | 6-0 | 6-9 | 7-6 | 8-2 | 9-6 | 11-3 | 13-10 | 18-0 | 23-8 | 45-1 |
| f3.5 | 2-1 | 2-7 | 3-2 | 4-4 | 5-7 | 6-11 | 8-3 | 9-8 | 11-3 | 12-10 | 16-4 | 22-6 | 35-11 | 89-6 | ∞ | ∞ |
| | 1-1 | 2-4 | 2-9 | 3-7 | 4-5 | 5-2 | 5-11 | 6-7 | 7-3 | 7-11 | 9-2 | 10-10 | 13-2 | 16-11 | 21-10 | 38-9 |
| f4 | 2-1 | 2-8 | 3-3 | 4-5 | 5-9 | 7-1 | 8-6 | 10-1 | 11-8 | 13-6 | 17-4 | 24-6 | 41-4 | 133-0 | ∞ | ∞ |
| | 1-1 | 2-4 | 2-9 | 3-7 | 4-4 | 5-1 | 5-9 | 6-5 | 7-1 | 7-8 | 8-10 | 10-5 | 12-7 | 15-11 | 20-2 | 33-11 |
| f4.5 | 2-1 | 2-8 | 3-3 | 4-6 | 5-10 | 7-3 | 8-7 | 10-5 | 12-3 | 14-2 | 18-6 | 26-11 | 48-7 | 260-0 | ∞ | ∞ |
| | 1-1 | 2-3 | 2-8 | 3-6 | 4-3 | 5-0 | 5-8 | 6-4 | 6-11 | 7-6 | 8-7 | 10-0 | 12-0 | 15-0 | 18-10 | 30-1 |
| f5.6 | 2-1 | 2-8 | 3-4 | 4-7 | 6-0 | 7-6 | 9-1 | 10-10 | 12-10 | 15-0 | 20-0 | 29-11 | 60-0 | ∞ | ∞ | ∞ |
| | 1-1 | 2-3 | 2-8 | 3-5 | 4-1 | 4-9 | 5-4 | 6-0 | 6-6 | 7-1 | 8-0 | 9-3 | 10-11 | 13-4 | 16-3 | 24-2 |
| f6.3 | 2-1 | 2-8 | 3-5 | 4-9 | 6-3 | 8-0 | 9-10 | 11-11 | 14-4 | 17-0 | 23-10 | 39-6 | 116-0 | ∞ | ∞ | ∞ |
| | 1-1 | 2-2 | 2-7 | 3-4 | 4-0 | 4-8 | 5-3 | 5-10 | 6-4 | 6-10 | 7-8 | 8-10 | 10-5 | 12-7 | 15-1 | 21-8 |
| f8 | 2-1 | 2-8 | 3-5 | 4-11 | 6-6 | 8-3 | 10-4 | 12-8 | 15-5 | 18-7 | 26-11 | 48-9 | 260-0 | ∞ | ∞ | ∞ |
| | 1-9 | 2-2 | 2-6 | 3-2 | 3-10 | 4-5 | 4-11 | 5-5 | 5-10 | 6-3 | 7-0 | 7-11 | 9-2 | 10-10 | 12-8 | 17-0 |
| f11 | 2-1 | 2-11 | 3-7 | 5-2 | 7-1 | 9-3 | 11-11 | 15-2 | 19-2 | 24-4 | 40-9 | 127-6 | ∞ | ∞ | ∞ | ∞ |
| | 1-8 | 2-1 | 2-5 | 3-0 | 3-6 | 4-0 | 4-5 | 4-10 | 5-2 | 5-8 | 6-1 | 6-9 | 7-7 | 8-9 | 9-10 | 12-4 |
| f16 | 2-4 | 3-1 | 3-11 | 5-11 | 8-5 | 11-8 | 16-2 | 22-9 | 33-4 | 53-0 | 44-0 | ∞ | ∞ | ∞ | ∞ | ∞ |
| | 1-7 | 1-11 | 2-2 | 2-8 | 3-1 | 3-6 | 3-10 | 4-1 | 4-4 | 4-7 | 4-11 | 5-3 | 5-11 | 6-7 | 7-3 | 8-6 |
| f22 | 2-7 | 3-6 | 4-7 | 7-7 | 12-4 | 20-8 | 40-7 | 148-0 | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ |
| | 1-6 | 1-9 | 2-0 | 2-5 | 2-9 | 3-0 | 3-3 | 3-5 | 3-8 | 3-9 | 4-1 | 4-4 | 4-8 | 5-1 | 5-6 | 6-2 |
| | 2-1 | 2-1 | 3-4 | 5-10 | 11-4 | 26-5 | 222-0 | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ |
| | 1-11 | 4-2 | 5-10 | 11-4 | 26-5 | 222-0 | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ |

IX.—DEPTH OF FIELD FOR LENSES OF 2 INCH (50 mm.) FOCAL LENGTH

| | | | | | | | | | | | | | | | | |
|-------|-------|-------|-------|-------|------|-------|-------|-------|--------|--------|-------|-------|-------|-------|-------|-------|
| f 1.5 | 1-11½ | 2-5½ | 2-11½ | 3-10½ | 4-9½ | 5-8½ | 6-7 | 7-5½ | 8-4 | 9-2 | 10-10 | 13-2½ | 16-11 | 23-7 | 34-5 | 111-0 |
| | 2-2½ | 3 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 20 | 30 | 50 | 111-0 |
| f 2 | 2-0½ | 2-½ | 3-1 | 4-1½ | 5-2½ | 6-4 | 7-5½ | 8-7½ | 9-9½ | 10-11½ | 13-5½ | 17-4 | 24-5 | 41-0 | 91-0 | 83-6 |
| | 1-11½ | 2-5½ | 2-10½ | 3-9½ | 4-8½ | 5-7½ | 6-5½ | 7-3½ | 8-1½ | 8-11 | 10-6 | 12-8 | 16-1 | 22-1 | 31-3 | 83-6 |
| f 2.5 | 2-0½ | 2-½ | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 20 | 30 | 50 | 66-8 |
| | 1-11½ | 2-5½ | 3-1½ | 4-2½ | 5-3½ | 6-5½ | 7-7½ | 8-10 | 9-11 | 11-4 | 14-0 | 18-3 | 26-4 | 47-0 | 125-0 | 66-8 |
| f 3 | 2-0½ | 2-½ | 3-1½ | 4-3 | 5-5 | 6-8½ | 7-10 | 8-12 | 9-15 | 11-9 | 14-7½ | 19-4 | 28-6 | 54-7 | 120-0 | 55-6 |
| | 1-11½ | 2-4½ | 2-10½ | 3-8½ | 4-7 | 5-5 | 6-2½ | 7-0 | 7-9 | 8-5½ | 9-10 | 11-9½ | 14-8½ | 19-6 | 26-4 | 55-6 |
| f 3.5 | 2-0½ | 2-½ | 3-2 | 4-3½ | 5-6 | 6-8½ | 8-0 | 9-4 | 10-9 | 12-2½ | 15-3½ | 20-6 | 31-3 | 65-6 | 500-0 | 47-7 |
| | 1-11 | 2-4½ | 2-9½ | 3-8½ | 4-6½ | 5-4 | 6-1½ | 6-10 | 7-7 | 8-3 | 9-7 | 11-5 | 14-1 | 18-5 | 24-4 | 47-7 |
| f 4 | 2-1 | 2-½ | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 20 | 30 | 50 | 41-8 |
| | 1-10½ | 2-4½ | 2-9½ | 3-7½ | 4-5½ | 5-3 | 6-0 | 6-8½ | 7-4½ | 8-0½ | 9-4 | 11-0 | 13-6 | 17-6 | 22-9 | 41-8 |
| f 4.5 | 2-1½ | 2-7½ | 3-2½ | 4-5 | 5-8½ | 7-0 | 8-5 | 9-10½ | 11-5½ | 13-2 | 16-10 | 23-5 | 38-4 | 107-0 | 50 | 37-1 |
| | 1-10½ | 2-4½ | 2-9½ | 3-7½ | 4-4½ | 5-2 | 5-10½ | 6-7 | 7-3 | 7-10½ | 9-1 | 10-8 | 13-0 | 16-7 | 21-3 | 37-1 |
| f 5.6 | 2-1½ | 2-7½ | 3-3½ | 4-5½ | 5-9½ | 7-2 | 8-7½ | 10-2½ | 11-10½ | 13-8 | 17-9 | 25-2 | 43-5 | 157-0 | 50 | 29-9 |
| | 1-10½ | 2-3½ | 2-8½ | 3-6½ | 4-3½ | 5-0 | 5-8 | 6-3½ | 6-11 | 7-5½ | 8-6½ | 10-0 | 12-0 | 14-1 | 18-8 | 29-9 |
| f 6.3 | 2-1½ | 2-7½ | 3-4 | 4-7½ | 6-0 | 7-6 | 9-2 | 10-11 | 12-11 | 15-1 | 20-1 | 30-3 | 61-0 | 50 | 50 | 26-8 |
| | 1-10½ | 2-3½ | 2-8½ | 3-5½ | 4-2½ | 4-10½ | 5-6½ | 6-2 | 6-8½ | 7-3½ | 8-3½ | 9-7 | 11-5 | 14-1 | 17-5 | 26-8 |
| f 8 | 2-2 | 2-8 | 3-4½ | 4-8½ | 6-2 | 7-9 | 9-6 | 11-5 | 13-7 | 16-0 | 21-10 | 34-3 | 80-0 | 50 | 50 | 20-10 |
| | 1-9½ | 2-2½ | 2-7½ | 3-4½ | 4-0½ | 4-8 | 5-3 | 5-9½ | 6-3½ | 6-9 | 7-7½ | 8-8½ | 10-2 | 12-3½ | 14-9 | 20-10 |
| f 11 | 2-2½ | 2-8½ | 3-5 | 4-9½ | 6-7 | 8-5 | 10-6½ | 13-0 | 15-10 | 19-3 | 28-4 | 53-6 | 500-0 | 50 | 50 | 15-1 |
| | 1-9½ | 2-1½ | 2-6 | 3-2 | 3-9 | 4-3½ | 4-9½ | 5-2½ | 5-7½ | 6-0 | 6-7 | 7-6 | 8-7 | 10-0 | 11-7 | 15-1 |
| f 16 | 2-3½ | 3-0 | 3-9 | 5-5½ | 7-6 | 9-11½ | 13-1 | 17-0 | 22-4 | 29-8 | 58-9 | 50 | 50 | 50 | 50 | 10-5 |
| | 1-8½ | 2-0½ | 2-4 | 2-10½ | 3-4½ | 3-9½ | 4-2½ | 4-6½ | 4-10 | 5-1½ | 5-7 | 6-2 | 6-10 | 7-9 | 8-7 | 10-5 |
| f 22 | 2-5½ | 3-2½ | 4-2½ | 6-6 | 9-7½ | 14-2 | 21-4 | 34-6 | 66-6 | 250-0 | 50 | 50 | 50 | 50 | 50 | 7-6 |
| | 1-7 | 1-10½ | 2-1½ | 2-7½ | 3-0 | 3-4 | 3-7½ | 3-10½ | 4-1 | 4-3½ | 4-7½ | 5-0 | 5-5½ | 6-0 | 6-6 | 7-6 |
| | 2 | 2½ | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 20 | 30 | 50 | 50 |
| | 2-8½ | 3-5 | 5-0 | 8-7 | 15-0 | 30-0 | 105-0 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 |

X.—DEPTH OF FIELD FOR LENSES OF 2½ INCH (62.5 mm.) FOCAL LENGTH

| | | | | | | | | | | | | | | | | |
|-------|-------|-------|-------|-------|-------|-------|--------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| f 1.5 | 2-11½ | 3-10½ | 4-9½ | 5-9 | 6-8 | 7-6½ | 8-5½ | 9-4 | 11-0½ | 13-6½ | 17-6 | 21-2 | 24-8 | 36-9 | 58-0 | 138-9 |
| | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 20 | 25 | 30 | 50 | 100 | ∞ |
| | 3-0½ | 4-1½ | 5-2½ | 6-3½ | 7-4½ | 8-6 | 9-7½ | 10-9½ | 13-1½ | 16-9½ | 23-4 | 30-5 | 38-3 | 78-2 | 351-0 | ∞ |
| f 2 | 2-11 | 3-10½ | 4-9½ | 5-8 | 6-6½ | 7-5 | 8-3½ | 9-1½ | 10-9 | 13-1½ | 16-9 | 20-2 | 23-4 | 33-9 | 51-0 | 104-2 |
| | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 20 | 25 | 30 | 50 | 100 | ∞ |
| | 3-1½ | 4-2 | 5-3 | 6-4½ | 7-6½ | 8-8 | 9-10 | 11-1 | 13-7 | 17-6 | 24-9 | 32-1½ | 42-0 | 96-2 | 2500 | ∞ |
| f 2.5 | 2-10½ | 3-9½ | 4-8½ | 5-7½ | 6-5½ | 7-3½ | 8-1½ | 8-1½ | 10-6 | 12-8½ | 16-1 | 19-3 | 22-1 | 31-3 | 45-6 | 83-4 |
| | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 20 | 25 | 30 | 50 | 100 | ∞ |
| | 3-1½ | 4-2½ | 5-3½ | 6-5½ | 7-7½ | 8-10 | 10-1 | 11-4½ | 14-0 | 18-3½ | 26-4 | 35-8 | 46-10 | 125-0 | ∞ | ∞ |
| f 3 | 2-10½ | 3-9½ | 4-8 | 5-6½ | 6-4½ | 7-2 | 7-11½ | 8-9 | 10-2½ | 12-4 | 15-6 | 18-4 | 21-0 | 29-1 | 41-0 | 69-6 |
| | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 20 | 25 | 30 | 50 | 100 | ∞ |
| | 3-1½ | 4-3 | 5-4½ | 6-6½ | 7-9½ | 9-0½ | 10-4 | 11-8 | 14-6 | 19-1½ | 28-1 | 39-0 | 52-9 | 173-6 | ∞ | ∞ |
| f 3.5 | 2-10½ | 3-9 | 4-7½ | 5-5½ | 6-3½ | 7-0½ | 7-9½ | 8-6½ | 10-0 | 12-0 | 15-0 | 17-7 | 20-0 | 27-2 | 37-4 | 59-6 |
| | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 20 | 25 | 30 | 50 | 100 | ∞ |
| | 3-1½ | 4-3½ | 5-5½ | 6-8 | 7-11 | 9-3 | 10-7 | 12-0 | 15-0 | 20-0 | 30-1½ | 43-0 | 60-6 | 313-6 | ∞ | ∞ |
| f 4 | 2-10 | 3-8½ | 4-6½ | 5-4½ | 6-2 | 6-11½ | 7-8 | 8-4½ | 9-9 | 11-7½ | 14-6 | 16-10 | 19-0 | 25-6 | 34-3 | 52-1 |
| | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 20 | 25 | 30 | 50 | 100 | ∞ |
| | 3-2½ | 4-4 | 5-6½ | 6-9½ | 8-1 | 9-5½ | 10-10½ | 12-4½ | 15-7 | 21-1 | 32-6 | 48-0 | 71-0 | 1250 | ∞ | ∞ |
| f 4.5 | 2-9½ | 3-8½ | 4-6½ | 5-3½ | 6-1 | 6-9½ | 7-6½ | 8-2½ | 9-6½ | 11-4 | 14-0 | 16-3 | 18-2 | 24-0 | 31-8 | 46-4 |
| | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 20 | 25 | 30 | 50 | 100 | ∞ |
| | 3-2½ | 4-4½ | 5-7½ | 6-10½ | 8-3 | 9-8 | 11-2 | 12-9 | 16-2 | 22-2 | 35-2 | 54-3 | 85-0 | ∞ | ∞ | ∞ |
| f 5.6 | 2-9½ | 3-7½ | 4-5 | 5-2 | 5-10½ | 6-7 | 7-3 | 7-10½ | 9-1 | 10-8½ | 13-0 | 15-0 | 16-7 | 21-4 | 27-0 | 37-3 |
| | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 20 | 25 | 30 | 50 | 100 | ∞ |
| | 3-3½ | 4-5½ | 5-9½ | 7-1½ | 8-7½ | 10-2 | 11-10½ | 13-8 | 17-9 | 25-2 | 43-2 | 76-0 | 154-0 | ∞ | ∞ | ∞ |
| f 6.3 | 2-9 | 3-6½ | 4-4 | 5-1 | 5-9½ | 6-5½ | 7-1 | 7-8½ | 8-10 | 10-4 | 12-6 | 14-3 | 15-9 | 20-0 | 25-0 | 33-4 |
| | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 20 | 25 | 30 | 50 | 100 | ∞ |
| | 3-3½ | 4-6½ | 5-10½ | 7-3½ | 8-10½ | 10-6 | 12-4 | 14-3½ | 18-9 | 27-3 | 50-0 | 100-0 | 300-0 | ∞ | ∞ | ∞ |
| f 8 | 2-8½ | 3-5½ | 4-2½ | 4-10½ | 5-6½ | 6-1½ | 6-8½ | 7-2½ | 8-2½ | 9-6 | 11-3 | 12-9 | 13-11 | 17-0 | 20-8 | 26-0 |
| | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 20 | 25 | 30 | 50 | 100 | ∞ |
| | 3-4½ | 4-8½ | 6-2½ | 7-9½ | 9-7 | 11-6½ | 13-9 | 16-3 | 22-3 | 35-6 | 86-8 | 650-0 | ∞ | ∞ | ∞ | ∞ |
| f 11 | 2-7 | 3-3½ | 3-11½ | 4-6½ | 5-1½ | 5-7½ | 5-6½ | 6-6½ | 7-4 | 8-4½ | 9-9 | 10-9 | 11-7 | 13-9 | 16-0 | 18-11 |
| | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 20 | 25 | 30 | 50 | 100 | ∞ |
| | 3-6½ | 5-1 | 6-9½ | 8-9½ | 11-1 | 13-10 | 17-2 | 21-2 | 32-10 | 72-6 | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ |
| f 16 | 2-5½ | 3-0½ | 3-7½ | 4-1½ | 4-6½ | 4-11½ | 5-4 | 5-8 | 6-3 | 6-11½ | 7-10½ | 8-6½ | 9-1 | 10-4 | 11-6 | 13-0 |
| | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 20 | 25 | 30 | 50 | 100 | ∞ |
| | 3-10½ | 5-9½ | 8-1½ | 11-2 | 15-2 | 20-9 | 29-9 | 43-6 | 156-0 | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ |
| f 22 | 2-3½ | 2-9½ | 3-3½ | 3-8 | 4-0½ | 4-4 | 4-7½ | 4-10½ | 5-3½ | 5-9½ | 6-5½ | 6-10½ | 7-2½ | 8-0 | 8-8 | 9-6 |
| | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 20 | 25 | 30 | 50 | 100 | ∞ |
| | 4-4½ | 6-11 | 10-7 | 16-4 | 26-6 | 50-6 | 171-0 | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ |

XI.—DEPTH OF FIELD FOR LENSES OF 3 INCH (75 mm.) FOCAL LENGTH

| | | | | | | | | | | | | | | | | |
|-------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|---------------------|---------------------|---------------------|--------------------|--------------------|---------------------|--------------------|--------------------|-------|--------------------|
| f 1.5 | 2-11 $\frac{1}{8}$ | 3-10 $\frac{1}{4}$ | 4-10 $\frac{1}{2}$ | 5-9 $\frac{1}{2}$ | 6-8 $\frac{1}{2}$ | 7-7 $\frac{1}{2}$ | 8-6 $\frac{1}{2}$ | 9-5 | 11-2 $\frac{1}{2}$ | 13-9 | 17-10 | 21-9 | 25-5 | 38-4 | 62-6 | 166-6 |
| | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 20 | 25 | 30 | 50 | 100 | OO |
| | 3-0 $\frac{1}{4}$ | 4-1 $\frac{1}{4}$ | 5-1 $\frac{1}{4}$ | 6-2 $\frac{1}{4}$ | 7-3 $\frac{1}{4}$ | 8-5 | 9-6 | 10-7 $\frac{1}{4}$ | 12-11 | 16-5 $\frac{1}{4}$ | 22-8 $\frac{1}{4}$ | 29-5 | 36-7 | 71-6 | 250-0 | OO |
| f 2 | 2-11 $\frac{1}{8}$ | 3-10 $\frac{1}{4}$ | 4-9 $\frac{1}{2}$ | 5-8 $\frac{1}{2}$ | 6-7 $\frac{1}{2}$ | 7-6 $\frac{1}{2}$ | 8-4 $\frac{1}{2}$ | 9-3 | 10-11 $\frac{1}{2}$ | 13-4 $\frac{1}{2}$ | 17-3 | 20-10 | 24-2 | 35-9 | 55-6 | 125-0 |
| | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 20 | 25 | 30 | 50 | 100 | OO |
| | 3-0 $\frac{1}{4}$ | 4-1 $\frac{1}{4}$ | 5-2 $\frac{1}{4}$ | 6-3 $\frac{1}{4}$ | 7-5 | 8-6 $\frac{1}{2}$ | 9-8 $\frac{1}{2}$ | 10-10 $\frac{1}{2}$ | 13-3 $\frac{1}{2}$ | 17-0 | 23-10 | 31-3 | 39-6 | 83-4 | 500-0 | OO |
| f 2.5 | 2-11 | 3-10 $\frac{1}{4}$ | 4-9 $\frac{1}{2}$ | 5-8 | 6-6 $\frac{1}{2}$ | 7-5 | 8-3 | 9-1 | 10-8 $\frac{1}{2}$ | 13-0 $\frac{1}{2}$ | 16-8 | 20-0 | 23-1 | 33-4 | 50-0 | 100-0 |
| | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 20 | 25 | 30 | 50 | 100 | OO |
| | 3-1 $\frac{1}{4}$ | 4-2 | 5-3 $\frac{1}{4}$ | 6-4 $\frac{1}{4}$ | 7-6 $\frac{1}{4}$ | 8-8 $\frac{1}{4}$ | 9-10 $\frac{1}{4}$ | 11-1 $\frac{1}{4}$ | 13-8 | 17-8 | 25-0 | 33-4 | 42-10 | 100-0 | OO | OO |
| f 3 | 2-10 $\frac{1}{2}$ | 3-9 $\frac{1}{2}$ | 4-8 $\frac{1}{2}$ | 5-7 $\frac{1}{2}$ | 6-5 $\frac{1}{2}$ | 7-3 $\frac{1}{2}$ | 8-1 $\frac{1}{2}$ | 9-1 | 10-6 | 12-8 $\frac{1}{2}$ | 16-1 | 19-3 | 22-1 | 31-3 | 45-6 | 83-4 |
| | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 20 | 25 | 30 | 50 | 100 | OO |
| | 3-1 $\frac{1}{4}$ | 4-2 $\frac{1}{4}$ | 5-4 | 6-5 $\frac{1}{4}$ | 7-7 $\frac{1}{4}$ | 8-10 | 10-1 | 11-4 $\frac{1}{4}$ | 14-0 | 18-4 | 26-4 | 35-9 | 47-0 | 125-0 | OO | OO |
| f 3.5 | 2-10 $\frac{1}{2}$ | 3-9 $\frac{1}{2}$ | 4-8 | 5-6 $\frac{1}{2}$ | 6-4 $\frac{1}{2}$ | 7-2 $\frac{1}{2}$ | 8-0 | 8-9 $\frac{1}{2}$ | 10-3 | 12-5 | 15-7 $\frac{1}{2}$ | 18-6 | 21-2 | 29-5 | 41-8 | 71-5 |
| | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 20 | 25 | 30 | 50 | 100 | OO |
| | 3-1 $\frac{1}{4}$ | 4-3 $\frac{1}{4}$ | 5-5 $\frac{1}{4}$ | 6-7 $\frac{1}{4}$ | 7-9 | 9-0 | 10-3 $\frac{1}{4}$ | 11-7 $\frac{1}{4}$ | 14-5 | 19-0 | 27-9 | 38-5 | 51-9 | 166-8 | OO | OO |
| f 4 | 2-10 $\frac{1}{2}$ | 3-9 $\frac{1}{2}$ | 4-7 $\frac{1}{2}$ | 5-5 $\frac{1}{2}$ | 6-3 $\frac{1}{2}$ | 7-1 | 7-10 $\frac{1}{2}$ | 8-7 $\frac{1}{2}$ | 10-1 | 12-1 | 15-2 | 17-10 | 20-3 | 27-9 | 38-6 | 62-6 |
| | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 20 | 25 | 30 | 50 | 100 | OO |
| | 3-1 $\frac{1}{4}$ | 4-3 $\frac{1}{4}$ | 5-5 $\frac{1}{4}$ | 6-7 $\frac{1}{4}$ | 7-10 $\frac{1}{4}$ | 9-2 | 10-6 | 11-10 $\frac{1}{4}$ | 14-10 | 19-8 $\frac{1}{4}$ | 29-5 | 41-8 | 57-9 | 250-0 | OO | OO |
| f 4.5 | 2-10 $\frac{1}{2}$ | 3-8 $\frac{1}{2}$ | 4-7 | 5-5 | 6-2 $\frac{1}{2}$ | 7-0 | 7-9 | 8-5 $\frac{1}{2}$ | 9-10 $\frac{1}{2}$ | 11-10 | 14-8 $\frac{1}{2}$ | 17-3 | 19-6 | 26-4 | 35-9 | 55-7 |
| | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 20 | 25 | 30 | 50 | 100 | OO |
| | 3-2 | 4-3 $\frac{1}{2}$ | 5-6 | 6-8 $\frac{1}{2}$ | 8-0 | 9-4 | 10-9 | 12-2 $\frac{1}{2}$ | 15-3 $\frac{1}{2}$ | 20-6 | 31-3 | 45-5 | 65-2 | 498-0 | OO | OO |
| f 5.6 | 2-9 $\frac{1}{2}$ | 3-8 | 4-6 | 5-3 $\frac{1}{2}$ | 6-0 $\frac{1}{2}$ | 6-9 $\frac{1}{2}$ | 7-6 | 8-2 | 9-5 $\frac{1}{2}$ | 11-2 $\frac{1}{2}$ | 13-9 $\frac{1}{2}$ | 16-0 | 17-11 | 23-7 | 30-10 | 44-7 |
| | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 20 | 25 | 30 | 50 | 100 | OO |
| | 3-2 $\frac{1}{4}$ | 4-4 $\frac{1}{4}$ | 5-7 $\frac{1}{4}$ | 6-11 $\frac{1}{4}$ | 8-3 $\frac{1}{4}$ | 9-9 | 11-3 | 12-11 | 16-5 | 22-7 | 36-3 | 57-0 | 91-8 | OO | OO | OO |
| f 6.3 | 2-9 $\frac{1}{2}$ | 3-7 $\frac{1}{2}$ | 4-5 $\frac{1}{2}$ | 5-2 $\frac{1}{2}$ | 5-11 $\frac{1}{2}$ | 6-8 | 7-4 | 8-0 | 9-2 $\frac{1}{2}$ | 10-11 | 13-4 | 15-4 $\frac{1}{2}$ | 17-1 $\frac{1}{2}$ | 22-5 | 28-6 | 40-0 |
| | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 20 | 25 | 30 | 50 | 100 | OO |
| | 3-2 $\frac{1}{4}$ | 4-5 $\frac{1}{4}$ | 5-8 $\frac{1}{4}$ | 7-0 $\frac{1}{4}$ | 8-6 | 10-0 | 11-7 $\frac{1}{4}$ | 13-4 | 17-1 $\frac{1}{4}$ | 24-0 | 40-0 | 66-8 | 120-0 | OO | OO | OO |
| f 8 | 2-8 $\frac{1}{2}$ | 3-6 $\frac{1}{2}$ | 4-3 $\frac{1}{2}$ | 5-0 $\frac{1}{2}$ | 5-8 $\frac{1}{2}$ | 6-4 $\frac{1}{2}$ | 7-0 | 7-7 | 8-8 | 10-1 $\frac{1}{2}$ | 12-0 $\frac{1}{2}$ | 13-10 $\frac{1}{2}$ | 15-3 $\frac{1}{2}$ | 19-3 | 23-10 | 31-3 |
| | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 20 | 25 | 30 | 50 | 100 | OO |
| | 3-3 $\frac{1}{4}$ | 4-7 | 5-11 $\frac{1}{4}$ | 7-5 | 9-0 | 10-9 | 12-7 $\frac{1}{4}$ | 14-8 $\frac{1}{4}$ | 19-6 | 28-10 | 55-6 | 125-0 | 750-0 | OO | OO | OO |
| f 11 | 2-7 $\frac{1}{2}$ | 3-4 $\frac{1}{2}$ | 4-1 $\frac{1}{2}$ | 4-9 | 5-4 $\frac{1}{2}$ | 5-11 | 6-5 $\frac{1}{2}$ | 6-11 $\frac{1}{2}$ | 7-10 $\frac{1}{2}$ | 9-0 $\frac{1}{2}$ | 10-7 $\frac{1}{2}$ | 11-11 | 12-11 | 15-7 $\frac{1}{2}$ | 18-6 | 22-9 |
| | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 20 | 25 | 30 | 50 | 100 | OO |
| | 3-5 $\frac{1}{4}$ | 4-10 $\frac{1}{4}$ | 6-5 | 8-1 $\frac{1}{4}$ | 10-1 $\frac{1}{4}$ | 12-4 | 14-10 $\frac{1}{4}$ | 17-10 | 25-4 | 44-0 | 165-6 | OO | OO | OO | OO | OO |
| f 16 | 2-6 $\frac{1}{2}$ | 3-2 $\frac{1}{2}$ | 3-9 $\frac{1}{2}$ | 4-4 | 4-10 | 5-3 $\frac{1}{2}$ | 5-8 $\frac{1}{2}$ | 6-1 $\frac{1}{2}$ | 6-9 $\frac{1}{2}$ | 7-7 $\frac{1}{2}$ | 8-9 $\frac{1}{2}$ | 9-7 $\frac{1}{2}$ | 10-3 $\frac{1}{2}$ | 11-11 | 13-6 | 15-7 $\frac{1}{2}$ |
| | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 20 | 25 | 30 | 50 | 100 | OO |
| | 3-8 $\frac{1}{4}$ | 5-4 $\frac{1}{4}$ | 7-4 $\frac{1}{4}$ | 9-9 | 12-8 | 16-4 $\frac{1}{4}$ | 21-3 | 27-9 | 51-8 | 375-0 | OO | OO | OO | OO | OO | OO |
| f 22 | 2-4 $\frac{1}{2}$ | 3-1 $\frac{1}{2}$ | 3-5 $\frac{1}{2}$ | 3-11 $\frac{1}{2}$ | 4-4 | 4-8 $\frac{1}{2}$ | 5-0 $\frac{1}{2}$ | 5-4 | 5-10 $\frac{1}{2}$ | 6-5 $\frac{1}{2}$ | 7-3 | 7-10 | 8-3 $\frac{1}{2}$ | 9-3 $\frac{1}{2}$ | 10-3 | 11-5 |
| | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 20 | 25 | 30 | 50 | 100 | OO |
| | 4-4 $\frac{1}{4}$ | 6-2 | 8-10 $\frac{1}{4}$ | 12-8 | 18-1 $\frac{1}{4}$ | 26-9 | 42-6 | 80-6 | OO | OO | OO | OO | OO | OO | OO | OO |

XIII.—DEPTH OF FIELD FOR LENSES OF 3 $\frac{1}{2}$ INCH (87.5 mm.) FOCAL LENGTH

| | | | | | | | | | | | | | | | | |
|------|--------------------|--------------------|---------------------|--------------------|--------------------|---------------------|--------------------|---------------------|---------------------|---------------------|--------------------|---------------------|--------------------|-------|-------|-------|
| f2 | 3.10 $\frac{1}{2}$ | 4.10 | 5.9 $\frac{1}{2}$ | 6.8 | 7.7 | 8.5 $\frac{1}{2}$ | 9.4 $\frac{1}{2}$ | 11.1 | 13.7 $\frac{1}{2}$ | 15.7 $\frac{1}{2}$ | 17.7 | 21.4 | 25.9 | 37.3 | 59.4 | 146.0 |
| | 4.1 $\frac{1}{2}$ | 5.2 | 6.3 | 7.4 | 8.5 $\frac{1}{2}$ | 9.7 | 10.9 | 13.1 | 16.8 | 19.10 $\frac{1}{2}$ | 23.2 | 30.2 | 37.9 | 76.0 | 318.6 | 00 |
| f2.5 | 3.10 $\frac{1}{2}$ | 4.9 $\frac{1}{2}$ | 5.8 $\frac{1}{2}$ | 6.7 $\frac{1}{2}$ | 7.5 $\frac{1}{2}$ | 8.4 | 9.2 $\frac{1}{2}$ | 10.10 $\frac{1}{2}$ | 13.3 $\frac{1}{2}$ | 15.2 $\frac{1}{2}$ | 17.1 | 20.7 | 23.10 | 35.0 | 53.10 | 116.8 |
| | 4.1 $\frac{1}{2}$ | 5.2 $\frac{1}{2}$ | 6.4 | 7.5 $\frac{1}{2}$ | 8.7 | 9.9 | 10.11 | 13.4 $\frac{1}{2}$ | 17.2 $\frac{1}{2}$ | 20.7 | 24.2 | 31.10 | 40.5 | 87.6 | 700.0 | 00 |
| f3 | 3.10 | 4.9 | 5.7 $\frac{1}{2}$ | 6.6 $\frac{1}{2}$ | 7.5 | 8.2 $\frac{1}{2}$ | 9.0 $\frac{1}{2}$ | 10.8 | 13.0 | 14.10 | 16.7 | 19.10 $\frac{1}{2}$ | 22.11 | 33.0 | 49.4 | 97.3 |
| | 4.2 | 5.3 $\frac{1}{2}$ | 6.4 $\frac{1}{2}$ | 7.6 $\frac{1}{2}$ | 8.8 $\frac{1}{2}$ | 9.11 | 11.2 | 13.8 | 17.9 | 21.4 | 25.2 | 33.8 | 43.5 | 103.0 | 100 | 00 |
| f3.5 | 3.9 $\frac{1}{2}$ | 4.8 $\frac{1}{2}$ | 6.7 $\frac{1}{2}$ | 6.5 $\frac{1}{2}$ | 7.3 $\frac{1}{2}$ | 8.1 $\frac{1}{2}$ | 8.11 | 10.6 | 12.8 $\frac{1}{2}$ | 14.5 | 16.1 | 19.3 | 22.1 | 31.3 | 45.6 | 83.4 |
| | 4.2 $\frac{1}{2}$ | 5.4 | 6.5 $\frac{1}{2}$ | 7.7 $\frac{1}{2}$ | 8.10 | 10.1 | 11.4 $\frac{1}{2}$ | 14.0 | 18.3 | 22.2 | 26.4 | 35.9 | 47.0 | 125.0 | 100 | 00 |
| f4 | 3.9 $\frac{1}{2}$ | 4.8 $\frac{1}{2}$ | 5.6 $\frac{1}{2}$ | 6.4 $\frac{1}{2}$ | 7.2 $\frac{1}{2}$ | 8.0 | 8.9 $\frac{1}{2}$ | 10.3 $\frac{1}{2}$ | 12.5 | 14.1 $\frac{1}{2}$ | 15.8 | 18.8 | 21.3 | 29.8 | 42.2 | 73.0 |
| | 4.2 $\frac{1}{2}$ | 5.4 $\frac{1}{2}$ | 6.6 $\frac{1}{2}$ | 7.9 | 9.0 | 10.3 | 11.7 | 14.4 | 18.10 $\frac{1}{2}$ | 23.0 | 27.7 | 47.8 | 51.0 | 159.0 | 100 | 00 |
| f4.5 | 3.9 $\frac{1}{2}$ | 4.7 $\frac{1}{2}$ | 5.6 | 6.4 | 7.1 $\frac{1}{2}$ | 7.11 | 8.8 | 10.1 $\frac{1}{2}$ | 12.2 | 13.9 $\frac{1}{2}$ | 15.3 $\frac{1}{2}$ | 18.0 | 20.6 | 28.3 | 39.4 | 64.10 |
| | 4.3 $\frac{1}{2}$ | 5.5 | 6.7 $\frac{1}{2}$ | 7.10 | 9.1 $\frac{1}{2}$ | 10.5 $\frac{1}{2}$ | 11.10 | 14.9 | 19.6 | 24.0 | 28.11 | 40.9 | 55.10 | 218.6 | 100 | 00 |
| f5.6 | 3.8 $\frac{1}{2}$ | 4.6 $\frac{1}{2}$ | 5.4 $\frac{1}{2}$ | 6.2 | 6.11 $\frac{1}{2}$ | 7.8 | 8.4 $\frac{1}{2}$ | 9.9 | 11.8 | 13.1 | 14.5 | 16.11 | 19.0 | 25.6 | 34.3 | 52.0 |
| | 4.4 | 5.6 $\frac{1}{2}$ | 6.9 $\frac{1}{2}$ | 8.1 $\frac{1}{2}$ | 9.5 $\frac{1}{2}$ | 10.10 $\frac{1}{2}$ | 12.4 $\frac{1}{2}$ | 15.7 | 21.1 | 26.4 | 32.6 | 48.0 | 70.10 | 1250 | 100 | 00 |
| f6.3 | 3.8 $\frac{1}{2}$ | 4.6 $\frac{1}{2}$ | 5.3 $\frac{1}{2}$ | 6.1 | 6.10 | 7.6 $\frac{1}{2}$ | 8.3 | 9.6 $\frac{1}{2}$ | 11.4 | 12.8 $\frac{1}{2}$ | 14.0 | 16.3 $\frac{1}{2}$ | 18.3 | 24.2 | 31.10 | 46.8 |
| | 4.4 $\frac{1}{2}$ | 5.7 $\frac{1}{2}$ | 6.10 $\frac{1}{2}$ | 8.2 $\frac{1}{2}$ | 9.8 | 11.2 | 12.9 | 16.2 | 22.1 | 28.0 | 35.0 | 53.10 | 85.0 | 100 | 100 | 00 |
| f8 | 3.7 $\frac{1}{2}$ | 4.4 $\frac{1}{2}$ | 5.1 $\frac{1}{2}$ | 5.10 $\frac{1}{2}$ | 6.7 | 7.2 $\frac{1}{2}$ | 7.10 $\frac{1}{2}$ | 9.0 $\frac{1}{2}$ | 10.7 $\frac{1}{2}$ | 11.10 | 12.11 | 14.10 | 16.5 $\frac{1}{2}$ | 21.1 | 26.9 | 36.6 |
| | 4.6 | 5.9 $\frac{1}{2}$ | 7.2 $\frac{1}{2}$ | 8.7 $\frac{1}{2}$ | 10.3 | 11.11 $\frac{1}{2}$ | 13.9 $\frac{1}{2}$ | 17.11 | 25.5 | 33.8 | 44.3 | 79.4 | 168.6 | 100 | 100 | 00 |
| f11 | 3.5 $\frac{1}{2}$ | 4.2 $\frac{1}{2}$ | 4.10 $\frac{1}{2}$ | 5.6 $\frac{1}{2}$ | 6.1 $\frac{1}{2}$ | 6.8 $\frac{1}{2}$ | 7.3 | 8.3 | 9.7 | 10.6 $\frac{1}{2}$ | 11.5 | 12.10 $\frac{1}{2}$ | 14.1 | 17.4 | 21.0 | 26.6 |
| | 4.8 $\frac{1}{2}$ | 6.2 | 7.9 | 9.6 | 11.5 $\frac{1}{2}$ | 13.7 $\frac{1}{2}$ | 16.0 $\frac{1}{2}$ | 21.11 | 34.7 | 51.6 | 81.6 | 441.6 | 100 | 100 | 100 | 00 |
| 116 | 3.3 $\frac{1}{2}$ | 3.11 | 4.6 $\frac{1}{2}$ | 5.0 $\frac{1}{2}$ | 5.6 $\frac{1}{2}$ | 6.0 $\frac{1}{2}$ | 6.5 $\frac{1}{2}$ | 7.2 $\frac{1}{2}$ | 8.3 | 8.11 | 9.6 $\frac{1}{2}$ | 10.7 | 11.4 | 13.4 | 15.6 | 18.3 |
| | 5.1 $\frac{1}{2}$ | 6.10 $\frac{1}{2}$ | 8.11 $\frac{1}{2}$ | 11.4 | 14.3 | 17.9 | 22.2 | 35.0 | 84.3 | 426.0 | 100 | 100 | 100 | 100 | 100 | 00 |
| f22 | 3.0 $\frac{1}{2}$ | 3.7 $\frac{1}{2}$ | 4.1 $\frac{1}{2}$ | 4.7 | 5.0 | 5.4 $\frac{1}{2}$ | 5.8 $\frac{1}{2}$ | 6.3 $\frac{1}{2}$ | 7.0 $\frac{1}{2}$ | 7.6 $\frac{1}{2}$ | 8.8 | 9.2 | 10.6 | 11.8 | 13.3 | 13.3 |
| | 5.8 $\frac{1}{2}$ | 8.0 $\frac{1}{2}$ | 10.11 $\frac{1}{2}$ | 14.10 | 20.2 | 28.0 | 40.0 | 135.6 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 00 |
| f32 | 2.9 $\frac{1}{2}$ | 3.2 $\frac{1}{2}$ | 3.7 $\frac{1}{2}$ | 3.11 $\frac{1}{2}$ | 4.3 $\frac{1}{2}$ | 4.6 $\frac{1}{2}$ | 4.9 $\frac{1}{2}$ | 5.2 $\frac{1}{2}$ | 5.8 $\frac{1}{2}$ | 6.0 | 6.3 $\frac{1}{2}$ | 6.8 $\frac{1}{2}$ | 7.0 $\frac{1}{2}$ | 7.9 | 8.5 | 9.2 |
| | 7.1 $\frac{1}{2}$ | 11.0 | 17.4 | 29.7 | 63.0 | 495.0 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 00 |

XIII.—DEPTH OF FIELD FOR LENSES OF 4 INCH (100 mm.) FOCAL LENGTH

| | | | | | | | | | | | | | | | | |
|--------------|--------------------|--------------------|-------------------|--------------------|---------------------|--------------------|---------------------|--------------------|---------------------|---------------------|---------------------|--------------------|--------------------|-------------------|-------|-------|
| <i>f</i> 2 | 3-11 | 4-10 $\frac{1}{2}$ | 5-9 $\frac{1}{2}$ | 6-8 $\frac{1}{2}$ | 7-7 $\frac{1}{2}$ | 8-6 $\frac{1}{2}$ | 9-5 | 11-2 $\frac{1}{2}$ | 13-9 | 15-5 | 17-10 | 21-9 | 25-5 | 38-6 | 62-6 | 166-8 |
| | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 50 | 100 | ∞ |
| | 4-1 $\frac{1}{2}$ | 5-1 $\frac{1}{2}$ | 6-2 $\frac{1}{2}$ | 7-3 $\frac{1}{2}$ | 8-5 | 9-6 | 10-7 $\frac{1}{2}$ | 12-11 | 16-5 $\frac{1}{2}$ | 18-11 | 22-9 | 29-5 | 36-7 | 71-6 | 250-0 | ∞ |
| <i>f</i> 2.5 | 3-10 $\frac{1}{2}$ | 4-9 $\frac{1}{2}$ | 5-9 | 6-7 $\frac{1}{2}$ | 7-6 $\frac{1}{2}$ | 8-5 | 9-3 $\frac{1}{2}$ | 11-0 | 13-6 | 15-11 | 17-5 | 21-1 | 24-6 | 36-5 | 57-2 | 133-4 |
| | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 50 | 100 | ∞ |
| | 4-1 $\frac{1}{2}$ | 5-2 $\frac{1}{2}$ | 6-3 $\frac{1}{2}$ | 7-4 $\frac{1}{2}$ | 8-6 $\frac{1}{2}$ | 9-7 $\frac{1}{2}$ | 10-9 $\frac{1}{2}$ | 13-2 | 16-11 | 19-6 | 23-6 $\frac{1}{2}$ | 30-6 $\frac{1}{2}$ | 38-9 | 80-0 | 400-0 | ∞ |
| <i>f</i> 3 | 3-10 $\frac{1}{2}$ | 4-9 $\frac{1}{2}$ | 5-8 $\frac{1}{2}$ | 6-7 | 7-5 $\frac{1}{2}$ | 8-4 | 9-2 | 10-10 | 13-2 $\frac{1}{2}$ | 14-9 | 16-11 $\frac{1}{2}$ | 20-5 | 23-7 $\frac{1}{2}$ | 34-6 | 52-8 | 111-0 |
| | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 50 | 100 | ∞ |
| | 4-1 $\frac{1}{2}$ | 5-2 $\frac{1}{2}$ | 6-4 | 7-5 $\frac{1}{2}$ | 8-7 $\frac{1}{2}$ | 9-9 $\frac{1}{2}$ | 10-11 $\frac{1}{2}$ | 13-5 $\frac{1}{2}$ | 17-4 | 20-1 | 24-4 | 32-3 | 41-1 | 91-0 | 1000 | ∞ |
| <i>f</i> 3.5 | 3-10 $\frac{1}{2}$ | 4-9 | 5-7 $\frac{1}{2}$ | 6-6 $\frac{1}{2}$ | 7-4 $\frac{1}{2}$ | 8-2 $\frac{1}{2}$ | 9-0 $\frac{1}{2}$ | 10-7 $\frac{1}{2}$ | 12-11 $\frac{1}{2}$ | 14-5 | 16-6 $\frac{1}{2}$ | 19-9 $\frac{1}{2}$ | 22-10 | 32-9 | 48-9 | 95-3 |
| | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 50 | 100 | ∞ |
| | 4-2 $\frac{1}{2}$ | 5-3 $\frac{1}{2}$ | 6-5 | 7-6 $\frac{1}{2}$ | 8-8 $\frac{1}{2}$ | 9-11 | 11-2 | 13-9 | 17-9 $\frac{1}{2}$ | 20-8 | 25-4 | 33-11 | 43-10 | 105-6 | ∞ | ∞ |
| <i>f</i> 4 | 3-10 $\frac{1}{2}$ | 4-8 $\frac{1}{2}$ | 5-7 $\frac{1}{2}$ | 6-5 $\frac{1}{2}$ | 7-3 $\frac{1}{2}$ | 8-1 $\frac{1}{2}$ | 8-11 | 10-6 | 12-8 $\frac{1}{2}$ | 14-4 $\frac{1}{2}$ | 16-1 $\frac{1}{2}$ | 19-3 | 22-1 | 31-3 | 45-6 | 83-4 |
| | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 50 | 100 | ∞ |
| | 4-2 $\frac{1}{2}$ | 5-3 $\frac{1}{2}$ | 6-5 $\frac{1}{2}$ | 7-7 $\frac{1}{2}$ | 8-10 | 10-1 | 11-4 $\frac{1}{2}$ | 14-0 | 18-3 $\frac{1}{2}$ | 21-4 | 26-4 | 35-9 | 46-10 | 125-0 | ∞ | ∞ |
| <i>f</i> 4.5 | 3-9 $\frac{1}{2}$ | 4-8 $\frac{1}{2}$ | 5-6 $\frac{1}{2}$ | 6-4 $\frac{1}{2}$ | 7-2 $\frac{1}{2}$ | 8-0 $\frac{1}{2}$ | 8-9 $\frac{1}{2}$ | 10-4 | 12-5 $\frac{1}{2}$ | 13-10 | 15-9 | 18-8 | 21-4 | 29-10 | 42-7 | 74-2 |
| | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 50 | 100 | ∞ |
| | 4-2 $\frac{1}{2}$ | 5-4 $\frac{1}{2}$ | 6-6 $\frac{1}{2}$ | 7-8 $\frac{1}{2}$ | 8-11 $\frac{1}{2}$ | 10-3 | 11-6 $\frac{1}{2}$ | 14-3 $\frac{1}{2}$ | 18-9 $\frac{1}{2}$ | 22-1 | 27-4 | 37-9 | 50-5 | 153-6 | ∞ | ∞ |
| <i>f</i> 5.6 | 3-9 | 4-7 $\frac{1}{2}$ | 5-5 $\frac{1}{2}$ | 6-3 | 7-0 $\frac{1}{2}$ | 7-9 $\frac{1}{2}$ | 8-6 $\frac{1}{2}$ | 10-0 | 11-11 $\frac{1}{2}$ | 13-2 $\frac{1}{2}$ | 14-11 $\frac{1}{2}$ | 18-5 | 19-11 | 27-2 | 37-4 | 59-6 |
| | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 50 | 100 | ∞ |
| | 4-3 $\frac{1}{2}$ | 5-5 $\frac{1}{2}$ | 6-8 | 7-11 $\frac{1}{2}$ | 9-3 | 10-7 | 12-0 | 15-0 $\frac{1}{2}$ | 20-1 | 23-9 | 30-2 | 43-0 | 60-6 | 312-6 | ∞ | ∞ |
| <i>f</i> 6.3 | 3-8 $\frac{1}{2}$ | 4-6 $\frac{1}{2}$ | 5-4 $\frac{1}{2}$ | 6-2 $\frac{1}{2}$ | 6-11 $\frac{1}{2}$ | 7-8 $\frac{1}{2}$ | 8-5 | 9-9 $\frac{1}{2}$ | 11-8 $\frac{1}{2}$ | 12-10 $\frac{1}{2}$ | 14-6 $\frac{1}{2}$ | 17-0 | 19-2 | 25-10 | 34-9 | 53-4 |
| | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 50 | 100 | ∞ |
| | 4-3 $\frac{1}{2}$ | 5-6 $\frac{1}{2}$ | 6-9 | 8-0 $\frac{1}{2}$ | 9-5 | 10-10 | 12-3 $\frac{1}{2}$ | 15-6 | 20-10 | 25-0 | 32-0 | 47-0 | 68-6 | 800-0 | ∞ | ∞ |
| <i>f</i> 8 | 3-7 $\frac{1}{2}$ | 4-5 $\frac{1}{2}$ | 5-3 | 6-0 | 6-8 $\frac{1}{2}$ | 7-4 $\frac{1}{2}$ | 8-0 $\frac{1}{2}$ | 9-3 $\frac{1}{2}$ | 11-0 | 12-1 | 13-6 | 15-7 $\frac{1}{2}$ | 17-6 | 22-9 | 29-5 | 41-8 |
| | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 50 | 100 | ∞ |
| | 4-5 | 5-8 $\frac{1}{2}$ | 7-0 | 8-5 | 9-10 $\frac{1}{2}$ | 11-5 $\frac{1}{2}$ | 13-2 | 16-10 | 23-5 | 23-8 | 38-5 | 62-6 | 107-0 | ∞ | ∞ | ∞ |
| <i>f</i> 11 | 3-6 $\frac{1}{2}$ | 4-3 $\frac{1}{2}$ | 5-0 $\frac{1}{2}$ | 5-8 $\frac{1}{2}$ | 6-4 | 6-11 $\frac{1}{2}$ | 7-6 $\frac{1}{2}$ | 8-7 $\frac{1}{2}$ | 10-0 $\frac{1}{2}$ | 10-11 | 12-0 $\frac{1}{2}$ | 13-8 $\frac{1}{2}$ | 15-0 | 18-11 | 23-4 | 30-4 |
| | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 50 | 100 | ∞ |
| | 4-7 $\frac{1}{2}$ | 5-11 $\frac{1}{2}$ | 7-5 $\frac{1}{2}$ | 9-1 $\frac{1}{2}$ | 10-10 $\frac{1}{2}$ | 12-9 $\frac{1}{2}$ | 14-11 | 19-10 | 29-8 | 38-8 | 58-9 | 143-0 | ∞ | ∞ | ∞ | ∞ |
| <i>f</i> 16 | 3-4 $\frac{1}{2}$ | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 50 | 100 |
| | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 50 | 100 | ∞ |
| | 4-11 $\frac{1}{2}$ | 6-7 | 8-5 | 10-6 $\frac{1}{2}$ | 12-11 $\frac{1}{2}$ | 15-10 | 19-3 | 23-4 | 53-6 | 92-6 | 500-0 | ∞ | ∞ | ∞ | ∞ | ∞ |
| <i>f</i> 22 | 3-2 | 3-9 | 4-3 $\frac{1}{2}$ | 4-9 $\frac{1}{2}$ | 5-3 | 5-8 | 6-0 $\frac{1}{2}$ | 6-8 $\frac{1}{2}$ | 7-6 | 8-7 | 9-5 | 10-1 | 11-8 | 13-2 | 15-2 | ∞ |
| | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 50 | 100 | ∞ |
| | 5-5 $\frac{1}{2}$ | 7-5 $\frac{1}{2}$ | 9-11 | 13-0 | 16-11 | 22-2 | 29-4 | 57-6 | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ |
| <i>f</i> 32 | 2-10 $\frac{1}{2}$ | 3-4 $\frac{1}{2}$ | 3-9 $\frac{1}{2}$ | 4-2 | 4-6 | 4-10 | 5-1 | 5-7 | 6-2 | 6-5 $\frac{1}{2}$ | 6-10 | 7-4 | 7-9 | 8-7 $\frac{1}{2}$ | 9-5 | 10-5 |
| | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 50 | 100 | ∞ |
| | 6-6 | 9-7 $\frac{1}{2}$ | 14-2 | 21-4 | 34-6 | 66-6 | 250-0 | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ |

XIV.—DEPTH OF FIELD FOR LENSES OF 4 INCH (112.5 mm.) FOCAL LENGTH

| | | | | | | | | | | | | | | | | |
|------|------|------|------|------|------|------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| f2 | 3-11 | 4-10 | 5-9 | 6-9 | 7-8 | 8-7 | 9-6 | 11-3 | 13-11 | 15-7 | 18-1 | 22-1 | 25-10 | 39-5 | 65-3 | 187-6 |
| | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 50 | 100 | ∞ |
| | 4-1 | 5-11 | 6-21 | 7-31 | 8-41 | 9-51 | 10-61 | 12-10 | 16-31 | 18-8 | 22-5 | 28-10 | 35-9 | 68-2 | 214-6 | ∞ |
| f2.5 | 3-10 | 4-10 | 5-9 | 6-8 | 7-7 | 8-6 | 9-4 | 11-1 | 13-7 | 15-3 | 17-8 | 21-5 | 25-0 | 37-6 | 60-0 | 150-0 |
| | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 50 | 100 | ∞ |
| | 4-1 | 5-2 | 6-3 | 7-4 | 8-5 | 9-7 | 10-8 | 13-0 | 16-8 | 19-2 | 23-1 | 30-0 | 37-6 | 75-0 | 300-0 | ∞ |
| f3 | 3-10 | 4-9 | 5-8 | 6-7 | 7-6 | 8-4 | 9-3 | 10-11 | 13-4 | 14-11 | 17-3 | 20-10 | 24-2 | 35-9 | 55-6 | 125-0 |
| | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 50 | 100 | ∞ |
| | 4-1 | 5-2 | 6-3 | 7-5 | 8-6 | 9-8 | 10-10 | 13-3 | 17-0 | 19-8 | 23-10 | 31-3 | 39-5 | 83-4 | 500-0 | ∞ |
| f3.5 | 3-10 | 4-9 | 5-8 | 6-7 | 7-5 | 8-3 | 9-2 | 10-9 | 13-2 | 14-8 | 17-0 | 20-3 | 23-5 | 34-2 | 51-9 | 107-2 |
| | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 50 | 100 | ∞ |
| | 4-1 | 5-3 | 6-4 | 7-6 | 8-7 | 9-10 | 11-0 | 13-6 | 17-6 | 20-0 | 24-7 | 32-7 | 41-8 | 93-10 | 1500 | ∞ |
| f4 | 3-10 | 4-9 | 5-7 | 6-6 | 7-4 | 8-2 | 9-0 | 10-7 | 12-1 | 14-4 | 16-6 | 19-9 | 22-9 | 32-7 | 48-5 | 93-10 |
| | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 50 | 100 | ∞ |
| | 4-1 | 5-3 | 6-5 | 7-6 | 8-9 | 9-11 | 11-2 | 13-9 | 17-10 | 20-9 | 25-5 | 34-1 | 44-0 | 107-0 | ∞ | ∞ |
| f4.5 | 3-9 | 4-8 | 5-7 | 6-5 | 7-3 | 8-1 | 8-11 | 10-6 | 12-8 | 14-1 | 16-1 | 19-3 | 22-1 | 31-3 | 45-6 | 83-5 |
| | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 50 | 100 | ∞ |
| | 4-2 | 5-3 | 6-5 | 7-7 | 8-10 | 10-1 | 11-4 | 14-0 | 18-3 | 21-4 | 26-4 | 35-9 | 46-10 | 125-0 | ∞ | ∞ |
| f5.6 | 3-9 | 4-8 | 5-6 | 6-4 | 7-1 | 8-1 | 8-11 | 10-2 | 12-3 | 13-7 | 15-8 | 18-3 | 20-9 | 28-8 | 40-0 | 67-0 |
| | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 50 | 100 | ∞ |
| | 4-3 | 5-5 | 6-7 | 7-10 | 9-1 | 10-5 | 11-9 | 14-7 | 19-4 | 22-9 | 28-6 | 40-0 | 54-4 | 197-0 | ∞ | ∞ |
| f6.3 | 3-9 | 4-7 | 5-5 | 6-3 | 7-0 | 7-10 | 8-7 | 10-0 | 12-0 | 13-3 | 15-0 | 17-8 | 20-0 | 27-3 | 37-6 | 60-0 |
| | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 50 | 100 | ∞ |
| | 4-3 | 5-5 | 6-8 | 7-11 | 9-2 | 10-7 | 12-0 | 15-0 | 20-0 | 23-11 | 30-0 | 42-11 | 60-0 | 300-0 | ∞ | ∞ |
| f8 | 3-8 | 4-6 | 5-4 | 6-1 | 6-10 | 7-6 | 8-3 | 9-6 | 11-4 | 12-6 | 14-0 | 16-4 | 18-4 | 24-3 | 31-10 | 46-11 |
| | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 50 | 100 | ∞ |
| | 4-4 | 5-7 | 6-10 | 8-2 | 9-7 | 11-1 | 12-8 | 16-1 | 22-1 | 26-8 | 34-10 | 53-6 | 83-4 | ∞ | ∞ | ∞ |
| f11 | 3-7 | 4-4 | 5-1 | 5-9 | 6-5 | 7-1 | 7-9 | 8-10 | 10-5 | 11-4 | 12-7 | 14-5 | 16-0 | 20-4 | 25-6 | 34-2 |
| | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 50 | 100 | ∞ |
| | 4-6 | 5-10 | 7-3 | 8-9 | 10-5 | 12-2 | 14-2 | 18-6 | 26-9 | 33-10 | 48-3 | 93-4 | 246-0 | ∞ | ∞ | ∞ |
| f16 | 3-5 | 4-1 | 4-9 | 5-4 | 6-11 | 6-6 | 7-0 | 7-11 | 9-2 | 9-10 | 10-10 | 12-1 | 13-2 | 16-0 | 19-0 | 23-6 |
| | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 50 | 100 | ∞ |
| | 4-9 | 6-4 | 8-0 | 9-11 | 12-1 | 14-7 | 17-5 | 24-6 | 41-6 | 61-6 | 134-6 | ∞ | ∞ | ∞ | ∞ | ∞ |
| f22 | 3-2 | 3-10 | 4-5 | 4-11 | 5-5 | 5-10 | 6-3 | 7-0 | 8-0 | 8-6 | 9-2 | 10-2 | 10-10 | 12-9 | 14-7 | 17-1 |
| | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 50 | 100 | ∞ |
| | 5-2 | 7-1 | 9-2 | 11-0 | 15-0 | 19-0 | 24-0 | 40-4 | 123-0 | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ |
| f32 | 2-11 | 3-6 | 3-11 | 4-4 | 4-9 | 5-1 | 5-5 | 5-11 | 6-7 | 6-11 | 7-5 | 8-0 | 8-5 | 9-6 | 10-6 | 11-9 |
| | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 50 | 100 | ∞ |
| | 6-0 | 8-8 | 12-3 | 17-4 | 25-1 | 38-6 | 67-0 | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ |

XV.—DEPTH OF FIELD FOR LENSES OF 5 INCH (125 mm.) FOCAL LENGTH

| | | | | | | | | | | | | | | | | |
|-------|--------------------|--------------------|-------------------|--------------------|---------------------|--------------------|--------------------|--------------------|---------------------|--------------------|--------------------|--------------------|-------|-------|-------|-------|
| f 2 | 4-10 $\frac{1}{2}$ | 5-10 | 6-9 $\frac{1}{2}$ | 7-8 $\frac{1}{2}$ | 8-7 $\frac{1}{2}$ | 9-6 $\frac{1}{2}$ | 11-4 | 14-0 | 15-8 | 18-3 | 22-4 | 26-3 | 33-7 | 40-4 | 67-6 | 208-6 |
| | 5-1 $\frac{1}{2}$ | 6-2 $\frac{1}{2}$ | 7-2 $\frac{1}{2}$ | 8-3 $\frac{1}{2}$ | 9-4 $\frac{1}{2}$ | 10-6 | 12-9 | 16-1 $\frac{1}{2}$ | 18-6 | 22-1 $\frac{1}{2}$ | 28-5 | 35-1 | 49-6 | 66-0 | 192-6 | 600 |
| f 2.5 | 4-10 $\frac{1}{2}$ | 5-9 $\frac{1}{2}$ | 6-8 $\frac{1}{2}$ | 7-7 $\frac{1}{2}$ | 8-6 $\frac{1}{2}$ | 9-5 | 11-2 | 13-9 | 15-5 | 17-10 | 21-9 | 25-5 | 32-3 | 38-5 | 62-6 | 166-8 |
| | 5-1 $\frac{1}{2}$ | 6-2 $\frac{1}{2}$ | 7-3 $\frac{1}{2}$ | 8-4 $\frac{1}{2}$ | 9-6 | 10-7 $\frac{1}{2}$ | 12-11 | 16-6 | 18-11 | 22-9 | 29-5 | 36-7 | 52-8 | 71-6 | 250-0 | 600 |
| f 3 | 4-10 | 5-9 | 6-8 | 7-6 $\frac{1}{2}$ | 8-5 $\frac{1}{2}$ | 9-4 | 11-0 $\frac{1}{2}$ | 13-6 $\frac{1}{2}$ | 15-1 $\frac{1}{2}$ | 17-6 | 21-2 | 24-8 | 31-0 | 36-9 | 57-9 | 139-0 |
| | 5-2 $\frac{1}{2}$ | 6-3 $\frac{1}{2}$ | 7-4 $\frac{1}{2}$ | 8-6 | 9-7 $\frac{1}{2}$ | 10-9 $\frac{1}{2}$ | 13-1 $\frac{1}{2}$ | 16-11 | 19-4 | 23-4 | 30-6 | 38-3 | 56-2 | 77-11 | 357-0 | 600 |
| f 3.5 | 4-9 $\frac{1}{2}$ | 5-8 $\frac{1}{2}$ | 6-7 $\frac{1}{2}$ | 7-6 | 8-4 $\frac{1}{2}$ | 9-2 $\frac{1}{2}$ | 10-11 | 13-4 | 14-10 $\frac{1}{2}$ | 17-1 $\frac{1}{2}$ | 20-8 | 24-0 | 29-11 | 35-3 | 54-6 | 119-1 |
| | 5-2 $\frac{1}{2}$ | 6-3 $\frac{1}{2}$ | 7-5 $\frac{1}{2}$ | 8-7 | 9-9 | 10-11 | 13-4 | 17-2 | 19-10 | 24-0 | 31-8 | 40-1 | 60-3 | 86-3 | 625-0 | 600 |
| f 4 | 4-9 $\frac{1}{2}$ | 5-8 | 6-6 $\frac{1}{2}$ | 7-5 $\frac{1}{2}$ | 8-3 $\frac{1}{2}$ | 9-1 $\frac{1}{2}$ | 10-9 | 13-1 | 14-7 $\frac{1}{2}$ | 16-9 | 20-2 | 23-4 | 28-10 | 33-10 | 51-0 | 104-4 |
| | 5-3 | 6-4 $\frac{1}{2}$ | 7-6 | 8-8 | 9-10 | 11-0 $\frac{1}{2}$ | 13-7 | 17-6 | 20-4 | 24-9 | 32-11 | 42-2 | 65-0 | 96-0 | 2500 | 600 |
| f 4.5 | 4-9 | 5-7 $\frac{1}{2}$ | 6-6 | 7-4 $\frac{1}{2}$ | 8-2 $\frac{1}{2}$ | 9-0 $\frac{1}{2}$ | 10-7 $\frac{1}{2}$ | 12-11 | 14-4 $\frac{1}{2}$ | 16-5 | 19-8 | 22-8 | 27-11 | 32-6 | 48-0 | 92-8 |
| | 5-3 $\frac{1}{2}$ | 6-5 | 7-7 | 8-9 $\frac{1}{2}$ | 9-11 $\frac{1}{2}$ | 11-2 $\frac{1}{2}$ | 13-9 $\frac{1}{2}$ | 17-11 | 20-10 | 25-6 | 34-3 | 44-4 | 70-5 | 108-6 | 600 | 600 |
| f 5.6 | 4-8 $\frac{1}{2}$ | 5-6 $\frac{1}{2}$ | 6-4 $\frac{1}{2}$ | 7-2 $\frac{1}{2}$ | 8-0 $\frac{1}{2}$ | 8-10 | 10-4 | 12-6 | 13-10 | 15-9 $\frac{1}{2}$ | 18-9 | 21-4 | 26-0 | 29-11 | 42-8 | 74-6 |
| | 5-4 $\frac{1}{2}$ | 6-6 $\frac{1}{2}$ | 7-8 $\frac{1}{2}$ | 8-11 $\frac{1}{2}$ | 10-3 | 11-6 $\frac{1}{2}$ | 14-4 | 18-9 | 22-0 | 27-4 | 37-8 | 50-3 | 86-6 | 152-0 | 600 | 600 |
| f 6.3 | 4-8 | 5-6 | 6-4 | 7-1 $\frac{1}{2}$ | 7-11 | 8-8 $\frac{1}{2}$ | 10-2 | 12-3 | 13-6 | 15-4 $\frac{1}{2}$ | 18-2 | 20-8 | 25-0 | 28-7 | 40-0 | 66-8 |
| | 5-5 | 6-7 | 7-10 | 9-1 | 10-5 | 11-9 | 14-8 | 19-4 | 22-10 | 28-7 | 40-0 | 54-7 | 100-0 | 200-0 | 600 | 600 |
| f 8 | 4-6 $\frac{1}{2}$ | 5-4 $\frac{1}{2}$ | 6-2 | 6-11 $\frac{1}{2}$ | 7-8 | 8-4 $\frac{1}{2}$ | 9-9 | 11-8 | 12-10 | 14-5 | 16-10 | 19-0 | 22-7 | 25-6 | 34-3 | 52-2 |
| | 5-6 $\frac{1}{2}$ | 6-9 $\frac{1}{2}$ | 8-1 | 9-5 $\frac{1}{2}$ | 10-10 $\frac{1}{2}$ | 12-4 $\frac{1}{2}$ | 15-8 | 21-1 | 25-3 | 32-5 | 48-0 | 70-10 | 172-0 | 1250 | 600 | 600 |
| f 11 | 4-5 | 5-2 | 5-11 | 6-7 $\frac{1}{2}$ | 7-3 $\frac{1}{2}$ | 7-11 | 9-1 $\frac{1}{2}$ | 10-9 | 11-9 | 13-1 | 15-1 | 16-9 | 19-6 | 21-7 | 27-6 | 37-11 |
| | 5-5 $\frac{1}{2}$ | 6-7 $\frac{1}{2}$ | 8-7 | 10-1 $\frac{1}{2}$ | 11-10 | 13-7 | 17-6 | 24-10 | 30-10 | 42-4 | 73-4 | 144-0 | 600 | 600 | 600 | 600 |
| f 16 | 4-2 $\frac{1}{2}$ | 4-10 $\frac{1}{2}$ | 5-6 $\frac{1}{2}$ | 6-1 $\frac{1}{2}$ | 6-8 $\frac{1}{2}$ | 7-3 | 8-2 $\frac{1}{2}$ | 9-6 | 10-3 | 11-4 | 12-9 | 13-11 | 15-9 | 17-2 | 20-8 | 26-1 |
| | 6-2 $\frac{1}{2}$ | 7-9 $\frac{1}{2}$ | 9-7 | 11-6 $\frac{1}{2}$ | 13-9 | 16-3 | 22-3 | 35-4 | 48-9 | 85-8 | 602-0 | 600 | 600 | 600 | 600 | 600 |
| f 22 | 3-11 $\frac{1}{2}$ | 4-6 $\frac{1}{2}$ | 5-1 $\frac{1}{2}$ | 5-7 $\frac{1}{2}$ | 6-1 | 6-6 $\frac{1}{2}$ | 7-4 | 8-4 $\frac{1}{2}$ | 9-0 | 9-9 | 10-9 $\frac{1}{2}$ | 11-7 $\frac{1}{2}$ | 12-10 | 13-9 | 16-0 | 19-0 |
| | 6-9 $\frac{1}{2}$ | 8-9 | 11-1 | 13-10 | 17-1 | 21-1 | 32-7 | 71-3 | 161-6 | 600 | 600 | 600 | 600 | 600 | 600 | 600 |
| f 32 | 3-7 $\frac{1}{2}$ | 4-1 $\frac{1}{2}$ | 4-6 $\frac{1}{2}$ | 4-11 $\frac{1}{2}$ | 5-3 $\frac{1}{2}$ | 5-8 | 6-3 | 6-11 $\frac{1}{2}$ | 7-4 $\frac{1}{2}$ | 7-10 $\frac{1}{2}$ | 8-6 $\frac{1}{2}$ | 9-1 | 9-10 | 10-4 | 11-6 | 13-0 |
| | 8-1 $\frac{1}{2}$ | 11-2 | 15-2 | 20-10 | 29-3 | 43-4 | 156-0 | 600 | 600 | 600 | 600 | 600 | 600 | 600 | 600 | 600 |

XVI.—DEPTH OF FIELD FOR LENSES OF 5 $\frac{1}{2}$ INCH (137.5 mm.) FOCAL LENGTH

| | | | | | | | | | | | | | | | | |
|--------|--------------------|--------------------|--------------------|--------------------|--------------------|---------------------|---------------------|--------------------|-------------------|-------|--------------------|--------------------|-------|-------|-------|--------|
| $f2$ | 4-10 $\frac{1}{2}$ | 5-10 $\frac{1}{2}$ | 6-9 $\frac{1}{2}$ | 7-8 $\frac{1}{2}$ | 8-8 | 9-7 | 11-4 $\frac{1}{2}$ | 14-1 | 15-10 | 18-5 | 22-6 | 26-6 | 34-0 | 41-0 | 69-8 | 229-3 |
| | 5-1 $\frac{1}{2}$ | 6-2 | 7-2 $\frac{1}{2}$ | 8-3 $\frac{1}{2}$ | 9-4 $\frac{1}{2}$ | 10-5 $\frac{1}{2}$ | 12-8 | 16-0 $\frac{1}{2}$ | 18-4 | 21-11 | 28-1 | 34-6 | 48-6 | 64-0 | 177-6 | OO |
| $f2.5$ | 4-10 $\frac{1}{2}$ | 5-9 $\frac{1}{2}$ | 6-9 | 7-8 | 8-7 | 9-6 | 11-3 | 13-10 | 15-7 | 18-0 | 22-0 | 25-10 | 32-10 | 39-3 | 64-9 | 183-4 |
| | 5-1 $\frac{1}{2}$ | 6-2 $\frac{1}{2}$ | 7-3 $\frac{1}{2}$ | 8-4 $\frac{1}{2}$ | 9-5 $\frac{1}{2}$ | 10-7 | 12-10 | 16-4 | 18-9 | 22-4 | 29-0 | 35-10 | 51-2 | 68-9 | 220-0 | OO |
| $f3$ | 4-10 | 5-9 $\frac{1}{2}$ | 6-8 $\frac{1}{2}$ | 7-7 | 8-6 | 9-4 $\frac{1}{2}$ | 11-1 $\frac{1}{2}$ | 13-8 | 15-4 | 17-8 | 21-6 | 25-0 | 31-8 | 37-8 | 60-5 | 152-9 |
| | 5-2 | 6-3 | 7-4 | 8-5 $\frac{1}{2}$ | 9-7 | 10-8 $\frac{1}{2}$ | 13-0 | 16-7 $\frac{1}{2}$ | 19-2 | 23-0 | 30-0 | 37-4 | 54-2 | 74-4 | 290-0 | OO |
| $f3.5$ | 4-9 $\frac{1}{2}$ | 5-9 | 6-7 $\frac{1}{2}$ | 7-6 $\frac{1}{2}$ | 8-5 | 9-3 $\frac{1}{2}$ | 11-0 | 13-5 $\frac{1}{2}$ | 15-1 | 17-4 | 21-0 | 24-5 | 30-7 | 36-2 | 56-8 | 131-0 |
| | 5-2 $\frac{1}{2}$ | 6-3 $\frac{1}{2}$ | 7-4 $\frac{1}{2}$ | 8-6 | 9-8 | 10-10 | 13-2 $\frac{1}{2}$ | 16-11 | 19-6 | 23-7 | 30-11 | 38-11 | 57-6 | 81-0 | 422-6 | OO |
| $f4$ | 4-9 $\frac{1}{2}$ | 5-8 $\frac{1}{2}$ | 6-7 | 7-5 $\frac{1}{2}$ | 8-4 | 9-2 $\frac{1}{2}$ | 10-10 $\frac{1}{2}$ | 13-3 | 14-10 | 17-0 | 20-6 | 23-9 | 29-8 | 34-10 | 53-6 | 114-7 |
| | 5-2 $\frac{1}{2}$ | 6-4 | 7-5 $\frac{1}{2}$ | 8-7 $\frac{1}{2}$ | 9-9 | 10-11 $\frac{1}{2}$ | 13-5 | 17-3 | 20-0 | 24-3 | 32-0 | 40-8 | 61-6 | 88-9 | 785 | OO |
| $f4.5$ | 4-9 $\frac{1}{2}$ | 5-8 | 6-6 $\frac{1}{2}$ | 7-5 | 8-3 | 9-1 $\frac{1}{2}$ | 10-9 | 13-1 | 14-7 | 16-9 | 20-1 | 23-2 | 28-8 | 33-6 | 50-5 | 101-10 |
| | 5-3 | 6-4 $\frac{1}{2}$ | 7-6 $\frac{1}{2}$ | 8-8 $\frac{1}{2}$ | 9-10 $\frac{1}{2}$ | 11-1 | 13-7 $\frac{1}{2}$ | 17-7 | 20-5 | 24-10 | 33-2 | 42-3 | 66-0 | 98-6 | OO | OO |
| $f5.6$ | 4-8 $\frac{1}{2}$ | 5-7 | 6-5 $\frac{1}{2}$ | 7-3 $\frac{1}{2}$ | 8-1 $\frac{1}{2}$ | 8-11 | 10-5 $\frac{1}{2}$ | 12-8 | 14-1 | 16-1 | 19-2 | 22-0 | 26-10 | 31-0 | 45-0 | 81-10 |
| | 5-4 | 6-5 $\frac{1}{2}$ | 7-8 | 8-10 $\frac{1}{2}$ | 11-5 | 14-1 | 18-4 | 21-6 | 26-6 | 36-0 | 47-4 | 78-3 | 128-8 | OO | OO | OO |
| $f6.3$ | 4-8 $\frac{1}{2}$ | 5-6 $\frac{1}{2}$ | 6-4 $\frac{1}{2}$ | 7-2 $\frac{1}{2}$ | 8-0 $\frac{1}{2}$ | 8-9 $\frac{1}{2}$ | 10-4 | 12-5 | 13-10 | 15-8 | 18-8 | 21-4 | 25-11 | 29-9 | 42-4 | 73-6 |
| | 5-4 $\frac{1}{2}$ | 6-6 $\frac{1}{2}$ | 7-9 | 8-11 $\frac{1}{2}$ | 10-3 | 11-7 | 14-4 | 18-10 | 22-1 | 27-6 | 37-11 | 50-8 | 87-9 | 156-6 | OO | OO |
| $f8$ | 4-7 $\frac{1}{2}$ | 5-5 $\frac{1}{2}$ | 6-3 | 7-0 | 7-9 $\frac{1}{2}$ | 8-6 | 9-11 | 11-11 | 13-1 | 14-10 | 17-5 | 19-9 | 23-7 | 26-9 | 36-6 | 57-4 |
| | 5-5 $\frac{1}{2}$ | 6-8 $\frac{1}{2}$ | 8-0 | 9-3 $\frac{1}{2}$ | 10-8 $\frac{1}{2}$ | 12-1 $\frac{1}{2}$ | 15-2 | 20-4 | 24-2 | 30-9 | 44-4 | 63-6 | 132-6 | 391-0 | OO | OO |
| $f11$ | 4-5 $\frac{1}{2}$ | 5-3 | 6-0 | 6-8 $\frac{1}{2}$ | 7-5 | 8-1 | 9-4 | 11-0 | 12-1 | 13-6 | 15-8 | 17-5 | 20-5 | 22-9 | 29-5 | 41-9 |
| | 5-8 $\frac{1}{2}$ | 7-0 | 8-5 | 9-11 | 11-6 | 13-2 | 16-10 | 23-5 | 28-9 | 38-6 | 62-6 | 107-0 | 1000 | OO | OO | OO |
| $f16$ | 4-3 | 4-11 $\frac{1}{2}$ | 5-7 $\frac{1}{2}$ | 6-3 | 6-10 | 7-5 | 8-5 $\frac{1}{2}$ | 9-10 | 10-8 | 11-9 | 13-4 | 14-8 | 16-8 | 18-3 | 22-3 | 28-8 |
| | 6-0 $\frac{1}{2}$ | 7-7 | 9-2 | 11-1 | 13-1 $\frac{1}{2}$ | 15-3 | 20-8 | 31-6 | 41-9 | 66-3 | 198-6 | OO | OO | OO | OO | OO |
| $f22$ | 4-0 $\frac{1}{2}$ | 4-8 | 5-3 | 5-9 $\frac{1}{2}$ | 6-3 $\frac{1}{2}$ | 6-9 | 7-7 $\frac{1}{2}$ | 8-9 | 9-4 | 10-2 | 11-4 $\frac{1}{2}$ | 12-3 $\frac{1}{2}$ | 13-8 | 14-9 | 17-3 | 20-11 |
| | 6-7 | 8-5 | 10-6 $\frac{1}{2}$ | 13-0 | 15-10 | 19-3 | 28-4 | 53-7 | 92-4 | 500-0 | OO | OO | OO | OO | OO | OO |
| $f32$ | 3-8 $\frac{1}{2}$ | 4-2 $\frac{1}{2}$ | 4-8 $\frac{1}{2}$ | 5-1 $\frac{1}{2}$ | 5-6 $\frac{1}{2}$ | 5-11 | 6-16 $\frac{1}{2}$ | 7-4 | 7-9 $\frac{1}{2}$ | 8-4 | 9-1 $\frac{1}{2}$ | 9-8 $\frac{1}{2}$ | 10-7 | 11-2 | 12-6 | 14-4 |
| | 7-8 | 10-4 | 13-8 | 18-2 | 24-2 | 33-0 | 73 | OO | OO | OO | OO | OO | OO | OO | OO | OO |

XVII.—DEPTH OF FIELD FOR LENSES OF 6 INCH (150 mm.) FOCAL LENGTH

| | | | | | | | | | | | | | | | | |
|-------------|-------|-------|-------|-------|-------|--------|--------|--------|-------|-------|-------|-------|-------|-------|-------|--------|
| f2 | 4-10½ | 5-10½ | 6-9½ | 7-9 | 8-8 | 9-7½ | 11-5½ | 14-2 | 15-11 | 18-6 | 22-9 | 26-10 | 34-6 | 41-8 | 71-6 | 250-0 |
| | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 40 | 50 | 100 | ∞ |
| | 5-1½ | 6-2 | 7-2½ | 8-3½ | 9-4½ | 10-5 | 12-7 | 15-11 | 18-3 | 21-9 | 27-9 | 34-1 | 47-7 | 62-6 | 166-8 | ∞ |
| f2.5 | 4-10½ | 5-10 | 6-9½ | 7-8½ | 8-7½ | 9-6 | 11-4 | 13-11½ | 15-8 | 18-2 | 22-9 | 26-1 | 33-4 | 40-0 | 66-8 | 200-0 |
| | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 40 | 50 | 100 | ∞ |
| | 5-1½ | 6-2½ | 7-3 | 8-4 | 9-5 | 10-6 | 12-9 | 16-2½ | 18-7 | 22-3 | 28-7 | 35-4 | 50-0 | 66-8 | 200-0 | ∞ |
| f3 | 4-10½ | 5-9½ | 6-8½ | 7-7½ | 8-6½ | 9-5 | 11-2 | 13-9 | 15-5 | 17-10 | 21-9 | 25-5 | 32-0 | 38-5 | 62-6 | 166-8 |
| | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 40 | 50 | 100 | ∞ |
| | 5-2 | 6-2½ | 7-3½ | 8-5 | 9-6 | 10-7½ | 12-11 | 16-6 | 18-1 | 22-9 | 29-5 | 36-7 | 52-8 | 71-5 | 250-0 | ∞ |
| f3.5 | 4-10 | 5-9 | 6-8 | 7-7 | 8-5½ | 9-4 | 11-1 | 13-7 | 15-2 | 17-6 | 21-3 | 24-10 | 31-3 | 37-1 | 58-9 | 142-11 |
| | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 40 | 50 | 100 | ∞ |
| | 5-2½ | 6-3½ | 7-4½ | 8-5½ | 9-7½ | 10-9 | 13-1 | 16-9 | 19-3½ | 23-3 | 30-4 | 37-10 | 55-6 | 77-0 | 333-4 | ∞ |
| f4 | 4-9½ | 5-8½ | 6-7½ | 7-6½ | 8-4½ | 9-3 | 10-11½ | 13-5 | 15-0 | 17-3 | 20-10 | 24-2 | 30-3 | 35-9 | 55-7 | 125-0 |
| | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 40 | 50 | 100 | ∞ |
| | 5-2½ | 6-3½ | 7-5 | 8-6½ | 9-8½ | 10-10½ | 13-3 | 17-0 | 19-8 | 23-10 | 31-3 | 39-5 | 58-9 | 83-4 | 500-0 | ∞ |
| f4.5 | 4-9½ | 5-8½ | 6-7 | 7-5½ | 8-4 | 9-2 | 10-10 | 13-2½ | 14-9 | 16-11 | 20-5 | 23-8 | 30-0 | 34-6 | 52-8 | 111-2 |
| | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 40 | 50 | 100 | ∞ |
| | 5-3 | 6-4 | 7-5½ | 8-7½ | 9-9½ | 11-0 | 13-5½ | 17-4 | 20-1 | 24-5 | 32-3 | 40-0 | 62-6 | 91-0 | ∞ | ∞ |
| f5.6 | 4-8½ | 5-7½ | 6-6 | 7-4 | 8-2 | 9-0 | 10-7 | 12-10 | 14-3 | 16-4 | 19-6 | 22-6 | 27-7 | 32-0 | 47-2 | 89-3 |
| | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 40 | 50 | 100 | ∞ |
| | 5-3½ | 6-5½ | 7-7 | 8-9½ | 10-0 | 11-3½ | 13-10½ | 18-0 | 21-0 | 25-9 | 34-9 | 45-2 | 72-6 | 113-6 | ∞ | ∞ |
| f6.3 | 4-8½ | 5-7 | 6-5½ | 7-3½ | 8-1 | 8-10½ | 10-5 | 12-2½ | 14-0 | 16-0 | 19-1 | 21-10 | 26-8 | 30-9 | 44-6 | 80-0 |
| | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 40 | 50 | 100 | ∞ |
| | 5-4 | 6-6 | 7-8 | 8-10½ | 10-1½ | 11-5 | 14-1½ | 18-4 | 21-7 | 26-8 | 36-4 | 48-0 | 80-0 | 133-4 | ∞ | ∞ |
| f8 | 4-7½ | 5-5½ | 6-3½ | 7-1 | 7-10½ | 8-7½ | 10-1 | 12-1 | 13-4 | 15-2 | 17-10 | 20-3 | 24-4 | 27-9 | 38-6 | 62-6 |
| | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 40 | 50 | 100 | ∞ |
| | 5-5½ | 6-7½ | 7-10½ | 9-2 | 10-6 | 11-11 | 14-10 | 19-9 | 23-4 | 29-5 | 41-8 | 57-8 | 111-0 | 250-0 | ∞ | ∞ |
| f11 | 4-6 | 5-3½ | 6-0½ | 6-9½ | 7-6 | 8-2½ | 9-6 | 11-3½ | 12-5 | 13-11 | 16-2 | 18-1 | 21-4 | 23-10 | 31-4 | 45-7 |
| | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 40 | 50 | 100 | ∞ |
| | 5-7½ | 6-11 | 8-3½ | 9-8½ | 11-2½ | 12-10 | 16-3½ | 22-4 | 27-1 | 35-8 | 55-6 | 87-6 | 326-6 | ∞ | ∞ | ∞ |
| f16 | 4-3½ | 5-0½ | 5-8½ | 6-4½ | 7-0 | 7-8 | 8-8 | 10-1½ | 11-0 | 12-2 | 13-11 | 15-4 | 17-6 | 19-3 | 23-10 | 31-2 |
| | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 40 | 50 | 100 | ∞ |
| | 5-11½ | 7-5 | 9-0 | 10-9 | 12-7½ | 13-10½ | 19-6 | 28-10 | 37-3 | 55-6 | 125-0 | 750-0 | ∞ | ∞ | ∞ | ∞ |
| f22 | 4-1½ | 4-9 | 5-4½ | 5-11 | 6-5½ | 7-0 | 7-10½ | 9-0½ | 9-9 | 10-8 | 11-11 | 13-0 | 14-6 | 15-8 | 18-5 | 22-10 |
| | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 40 | 50 | 100 | ∞ |
| | 6-5 | 8-1½ | 10-1 | 12-4 | 14-10 | 17-10 | 25-4 | 43-9 | 66-8 | 161-0 | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ |
| f32 | 3-9½ | 4-4 | 4-10 | 5-3½ | 5-8½ | 6-1 | 6-9½ | 7-8 | 8-1½ | 8-9 | 9-7 | 10-3 | 11-3 | 11-10 | 13-6 | 15-7 |
| | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 40 | 50 | 100 | ∞ |
| | 7-4½ | 9-9 | 12-9 | 16-5 | 21-4 | 27-10 | 52-3 | 400-0 | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ |

XVIII.—DEPTH OF FIELD FOR LENSES OF 7 INCH (175 mm.) FOCAL LENGTH

| | | | | | | | | | | | | | | | | |
|-------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|---------------------|---------------------|--------------------|-------|--------------------|-------|-------|-------|-------|
| f 2 | 5-10 $\frac{1}{2}$ | 6-10 | 7-9 $\frac{1}{2}$ | 8-8 $\frac{1}{2}$ | 9-8 | 11-6 $\frac{1}{2}$ | 14-3 | 16-1 | 18-8 $\frac{1}{2}$ | 23-0 | 27-2 | 35-2 | 42-8 | 74-6 | 118-6 | 291-8 |
| | 6-1 $\frac{1}{2}$ | 7-2 | 8-2 $\frac{1}{2}$ | 9-3 $\frac{1}{2}$ | 10-4 $\frac{1}{2}$ | 12-6 $\frac{1}{2}$ | 15-10 | 18-0 | 21-6 | 27-4 | 33-6 | 44-6 | 60-6 | 152-0 | 636-6 | 00 |
| f 2.5 | 5-10 $\frac{1}{2}$ | 6-9 $\frac{1}{2}$ | 7-8 $\frac{1}{2}$ | 8-8 | 9-7 | 11-5 | 14-1 | 15-10 | 18-5 | 22-7 | 26-7 | 34-2 | 41-2 | 70-0 | 92-4 | 233-4 |
| | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 40 | 50 | 100 | 200 | 00 |
| f 3 | 6-2 | 7-2 $\frac{1}{2}$ | 8-3 $\frac{1}{2}$ | 9-4 $\frac{1}{2}$ | 10-5 $\frac{1}{2}$ | 12-8 | 16-0 | 18-4 | 21-10 $\frac{1}{2}$ | 28-0 | 34-5 | 48-4 | 63-8 | 175-0 | 1400 | 00 |
| | 5-10 | 6-9 | 7-8 $\frac{1}{2}$ | 8-7 $\frac{1}{2}$ | 9-6 | 11-3 $\frac{1}{2}$ | 13-11 | 15-7 $\frac{1}{2}$ | 18-2 | 22-2 | 26-0 | 33-4 | 39-9 | 66-0 | 98-8 | 194-3 |
| | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 40 | 50 | 100 | 200 | 00 |
| f 3.5 | 6-2 $\frac{1}{2}$ | 7-3 $\frac{1}{2}$ | 8-4 | 9-5 $\frac{1}{2}$ | 10-6 $\frac{1}{2}$ | 12-9 $\frac{1}{2}$ | 16-3 | 18-7 $\frac{1}{2}$ | 22-3 | 28-8 | 35-6 | 50-4 | 67-4 | 206-0 | 00 | 00 |
| | 5-9 $\frac{1}{2}$ | 6-8 $\frac{1}{2}$ | 7-7 $\frac{1}{2}$ | 8-6 $\frac{1}{2}$ | 9-5 | 11-2 $\frac{1}{2}$ | 13-9 | 15-5 | 17-10 $\frac{1}{2}$ | 21-9 | 25-5 | 32-3 | 38-6 | 62-6 | 91-0 | 166-9 |
| | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 40 | 50 | 100 | 200 | 00 |
| f 4 | 6-2 $\frac{1}{2}$ | 7-3 $\frac{1}{2}$ | 8-5 | 9-6 | 10-7 $\frac{1}{2}$ | 12-11 | 16-5 $\frac{1}{2}$ | 18-11 | 22-9 | 29-5 | 36-7 | 52-8 | 71-6 | 250-0 | 00 | 00 |
| | 5-9 | 6-8 $\frac{1}{2}$ | 7-7 | 8-5 $\frac{1}{2}$ | 9-4 $\frac{1}{2}$ | 11-1 | 13-7 | 15-3 | 17-7 | 21-4 | 24-11 | 31-4 $\frac{1}{2}$ | 37-3 | 59-4 | 84-6 | 146-0 |
| | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 40 | 50 | 100 | 200 | 00 |
| f 4.5 | 6-3 | 7-4 $\frac{1}{2}$ | 8-5 $\frac{1}{2}$ | 9-7 | 10-9 | 13-1 | 16-8 | 19-3 | 23-2 | 30-2 | 37-9 | 55-0 | 76-0 | 318-0 | 00 | 00 |
| | 5-8 $\frac{1}{2}$ | 6-7 $\frac{1}{2}$ | 7-6 $\frac{1}{2}$ | 8-5 | 9-3 $\frac{1}{2}$ | 11-0 | 13-5 | 15-0 | 17-4 | 21-0 | 24-4 | 30-8 | 36-0 | 56-6 | 78-9 | 129-9 |
| | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 40 | 50 | 100 | 200 | 00 |
| f 5.6 | 6-3 $\frac{1}{2}$ | 7-4 $\frac{1}{2}$ | 8-6 $\frac{1}{2}$ | 9-8 | 10-10 | 13-2 $\frac{1}{2}$ | 17-0 | 19-7 | 23-8 | 31-0 | 39-0 | 57-10 | 81-6 | 436-0 | 00 | 00 |
| | 5-8 | 6-8 $\frac{1}{2}$ | 7-5 | 8-3 $\frac{1}{2}$ | 9-1 $\frac{1}{2}$ | 10-9 | 13-1 | 14-7 | 16-9 | 20-2 | 23-4 | 28-11 | 33-9 | 51-0 | 68-6 | 104-3 |
| | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 40 | 50 | 100 | 200 | 00 |
| f 6.3 | 6-4 $\frac{1}{2}$ | 7-6 | 8-8 | 9-10 $\frac{1}{2}$ | 11-0 $\frac{1}{2}$ | 13-7 | 17-6 | 20-4 | 24-9 | 32-11 | 42-2 | 65-0 | 96-0 | 2500 | 00 | 00 |
| | 5-7 $\frac{1}{2}$ | 6-6 | 7-4 $\frac{1}{2}$ | 8-2 $\frac{1}{2}$ | 9-0 $\frac{1}{2}$ | 10-7 $\frac{1}{2}$ | 12-11 | 14-4 | 16-5 | 19-8 | 22-6 | 27-11 | 32-6 | 48-0 | 63-4 | 92-6 |
| | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 40 | 50 | 100 | 200 | 00 |
| f 8 | 6-5 | 7-7 | 8-9 | 9-11 $\frac{1}{2}$ | 11-2 $\frac{1}{2}$ | 13-9 $\frac{1}{2}$ | 17-11 | 20-10 | 25-6 | 34-3 | 44-5 | 70-5 | 109-0 | 00 | 00 | 00 |
| | 5-6 $\frac{1}{2}$ | 6-4 $\frac{1}{2}$ | 7-2 $\frac{1}{2}$ | 8-0 | 8-9 $\frac{1}{2}$ | 10-3 $\frac{1}{2}$ | 12-5 | 13-9 $\frac{1}{2}$ | 15-8 | 18-8 | 21-3 | 25-10 | 29-6 | 42-2 | 53-6 | 73-0 |
| | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 40 | 50 | 100 | 200 | 00 |
| f 11 | 6-6 $\frac{1}{2}$ | 7-9 | 9-0 | 10-3 | 11-7 | 14-4 | 18-10 | 22-2 | 27-7 | 38-0 | 51-0 | 88-6 | 159-0 | 00 | 00 | 00 |
| | 5-4 $\frac{1}{2}$ | 6-2 $\frac{1}{2}$ | 6-11 $\frac{1}{2}$ | 7-8 $\frac{1}{2}$ | 8-5 | 9-9 $\frac{1}{2}$ | 11-8 | 12-10 $\frac{1}{2}$ | 14-6 | 17-0 | 19-2 | 22-9 | 25-9 | 34-8 | 42-0 | 53-0 |
| | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 40 | 50 | 100 | 200 | 00 |
| f 16 | 6-9 $\frac{1}{2}$ | 8-0 $\frac{1}{2}$ | 9-5 | 10-10 | 12-4 | 15-6 | 20-11 | 25-0 | 32-1 | 47-4 | 69-2 | 163-0 | 883-6 | 00 | 00 | 00 |
| | 5-11 | 5-10 $\frac{1}{2}$ | 6-6 $\frac{1}{2}$ | 7-2 $\frac{1}{2}$ | 7-10 | 9-0 | 10-7 $\frac{1}{2}$ | 11-7 | 12-11 | 14-10 | 16-5 | 19-1 | 21-1 | 26-9 | 30-10 | 36-6 |
| | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 40 | 50 | 100 | 200 | 00 |
| f 22 | 7-2 $\frac{1}{2}$ | 8-8 | 10-3 | 12-0 | 13-9 $\frac{1}{2}$ | 17-10 | 25-6 | 31-10 | 44-3 | 79-5 | 168-6 | 00 | 00 | 00 | 00 | 00 |
| | 4-10 $\frac{1}{2}$ | 5-6 $\frac{1}{2}$ | 6-1 $\frac{1}{2}$ | 6-8 $\frac{1}{2}$ | 7-3 | 8-3 | 9-7 | 10-4 | 11-5 | 12-10 | 14-1 | 15-11 | 17-4 | 21-0 | 23-5 | 26-6 |
| | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 40 | 50 | 100 | 200 | 00 |
| f 32 | 7-9 | 9-6 | 11-5 $\frac{1}{2}$ | 13-7 $\frac{1}{2}$ | 16-1 | 21-11 | 34-7 | 47-6 | 81-6 | 441-6 | 00 | 00 | 00 | 00 | 00 | 00 |
| | 4-6 $\frac{1}{2}$ | 5-0 $\frac{1}{2}$ | 5-6 $\frac{1}{2}$ | 6-0 $\frac{1}{2}$ | 6-5 $\frac{1}{2}$ | 7-3 | 8-3 | 8-9 $\frac{1}{2}$ | 9-6 $\frac{1}{2}$ | 10-6 $\frac{1}{2}$ | 11-4 | 12-6 | 13-4 | 15-5 | 16-9 | 18-3 |
| | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 40 | 50 | 100 | 200 | 00 |
| | 8-11 $\frac{1}{2}$ | 11-4 $\frac{1}{2}$ | 14-3 | 17-9 | 22-2 | 35-0 | 84-2 | 248-6 | 00 | 00 | 00 | 00 | 00 | 00 | 00 | 00 |

XIX.—DEPTH OF FIELD FOR LENSES OF 8 INCH (200 mm.) FOCAL LENGTH

| | | | | | | | | | | | | | | | | |
|--------|--------------------|---------------------|--------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|-----------------------|-----------------------|-----------------------|
| $f2$ | 6-10 $\frac{1}{2}$ | 7-9 $\frac{1}{2}$ | 8-9 | 9-8 $\frac{1}{2}$ | 11-7 | 14-4 | 16-2 | 18-10 $\frac{1}{2}$ | 23-3 | 27-7 | 35-9 | 43-6 | 50-10 | 77-0 | 125-0 | 333-4 |
| | 7-1 $\frac{1}{2}$ | 8-2 $\frac{1}{2}$ | 9-3 | 10-3 $\frac{1}{2}$ | 12-5 $\frac{1}{2}$ | 15-8 $\frac{1}{2}$ | 17-11 | 21-3 | 27-0 | 32-9 | 45-6 | 58-10 | 73-0 | 143-0 | 500-0 | 120 |
| $f2.5$ | 6-10 | 7-9 $\frac{1}{2}$ | 8-8 $\frac{1}{2}$ | 9-7 $\frac{1}{2}$ | 11-6 | 14-2 $\frac{1}{2}$ | 16-0 | 18-7 | 22-10 | 27-0 | 34-10 | 42-1 | 49-0 | 72-9 | 114-0 | 266-8 |
| | 7-8 | 8-9 | 9-10 | 10-11 | 12-15 | 15-17 | 17-20 | 20-25 | 25-30 | 30-40 | 40-50 | 50-60 | 60-70 | 100-100 | 200-200 | 500-800 |
| | 7-2 $\frac{1}{2}$ | 8-3 | 9-3 $\frac{1}{2}$ | 10-4 $\frac{1}{2}$ | 12-7 | 15-11 | 18-2 | 21-7 | 27-7 | 33-10 | 47-1 | 61-8 | 77-6 | 160-0 | 800-0 | 200 |
| $f3$ | 6-9 $\frac{1}{2}$ | 7-8 $\frac{1}{2}$ | 8-7 $\frac{1}{2}$ | 9-6 $\frac{1}{2}$ | 11-5 $\frac{1}{2}$ | 14-0 $\frac{1}{2}$ | 15-9 $\frac{1}{2}$ | 18-4 | 22-6 | 26-5 | 33-10 | 40-10 | 47-3 | 69-0 | 105-0 | 222-0 |
| | 7-8 $\frac{1}{2}$ | 8-9 $\frac{1}{2}$ | 9-10 $\frac{1}{2}$ | 10-11 $\frac{1}{2}$ | 12-15 $\frac{1}{2}$ | 15-17 $\frac{1}{2}$ | 17-20 $\frac{1}{2}$ | 20-25 $\frac{1}{2}$ | 25-30 $\frac{1}{2}$ | 30-40 $\frac{1}{2}$ | 40-50 $\frac{1}{2}$ | 50-60 $\frac{1}{2}$ | 60-70 $\frac{1}{2}$ | 100-100 $\frac{1}{2}$ | 200-200 $\frac{1}{2}$ | 500-800 $\frac{1}{2}$ |
| | 7-2 $\frac{1}{2}$ | 8-3 $\frac{1}{2}$ | 9-4 $\frac{1}{2}$ | 10-5 $\frac{1}{2}$ | 12-8 | 16-1 | 18-5 | 22-0 | 28-2 | 34-8 | 48-9 | 64-7 | 82-3 | 182-0 | 2020 | 500 |
| $f3.5$ | 6-9 | 7-8 | 8-7 | 9-6 | 11-4 $\frac{1}{2}$ | 13-11 | 15-7 $\frac{1}{2}$ | 18-1 | 22-1 | 25-11 | 33-0 | 39-7 | 45-8 | 65-6 | 97-6 | 190-6 |
| | 7-8 | 8-9 | 9-10 | 10-11 | 12-15 | 15-17 | 17-20 | 20-25 | 25-30 | 30-40 | 40-50 | 50-60 | 60-70 | 100-100 | 200-200 | 500-800 |
| | 7-3 $\frac{1}{2}$ | 8-4 | 9-5 $\frac{1}{2}$ | 10-7 | 12-9 $\frac{1}{2}$ | 16-3 | 18-8 | 22-4 | 28-10 | 35-7 | 50-7 | 67-11 | 87-9 | 210-6 | 500 | 200 |
| $f4$ | 6-8 $\frac{1}{2}$ | 7-7 $\frac{1}{2}$ | 8-6 $\frac{1}{2}$ | 9-5 | 11-2 $\frac{1}{2}$ | 13-9 | 15-5 | 17-10 | 21-9 | 25-5 | 32-3 | 38-6 | 44-1 | 62-6 | 91-0 | 166-8 |
| | 7-7 $\frac{1}{2}$ | 8-8 | 9-9 | 10-10 | 12-15 | 15-17 | 17-20 | 20-25 | 25-30 | 30-40 | 40-50 | 50-60 | 60-70 | 100-100 | 200-200 | 500-800 |
| | 7-3 $\frac{1}{2}$ | 8-5 | 9-6 | 10-7 $\frac{1}{2}$ | 12-11 | 16-5 $\frac{1}{2}$ | 18-11 | 22-9 | 29-5 | 36-7 | 52-8 | 71-5 | 93-9 | 250-0 | 500 | 200 |
| $f4.5$ | 6-8 $\frac{1}{2}$ | 7-7 $\frac{1}{2}$ | 8-6 | 9-4 $\frac{1}{2}$ | 11-1 | 13-7 $\frac{1}{2}$ | 15-3 | 17-7 $\frac{1}{2}$ | 21-5 | 25-0 | 31-6 | 37-6 | 42-9 | 59-9 | 85-0 | 148-3 |
| | 7-8 | 8-9 | 9-10 | 10-11 | 12-15 | 15-17 | 17-20 | 20-25 | 25-30 | 30-40 | 40-50 | 50-60 | 60-70 | 100-100 | 200-200 | 500-800 |
| | 7-4 $\frac{1}{2}$ | 8-5 $\frac{1}{2}$ | 9-7 | 10-8 $\frac{1}{2}$ | 13-0 $\frac{1}{2}$ | 16-8 | 19-2 | 23-1 | 30-0 | 37-7 | 54-7 | 75-6 | 101-0 | 304-6 | 500 | 200 |
| $f5.6$ | 6-7 $\frac{1}{2}$ | 7-6 | 8-4 $\frac{1}{2}$ | 9-2 $\frac{1}{2}$ | 10-11 | 13-4 | 14-10 $\frac{1}{2}$ | 17-1 | 20-8 | 24-0 | 30-0 | 35-3 | 39-11 | 54-4 | 74-6 | 119-0 |
| | 7-8 | 8-9 | 9-10 | 10-11 | 12-15 | 15-17 | 17-20 | 20-25 | 25-30 | 30-40 | 40-50 | 50-60 | 60-70 | 100-100 | 200-200 | 500-800 |
| | 7-5 $\frac{1}{2}$ | 8-7 | 9-9 | 10-11 | 13-4 | 17-2 | 19-10 | 24-1 | 31-8 | 40-0 | 60-3 | 86-3 | 121-0 | 625-0 | 500 | 200 |
| $f6.3$ | 6-7 | 7-5 $\frac{1}{2}$ | 8-3 $\frac{1}{2}$ | 9-2 | 10-10 | 13-2 | 14-8 | 16-10 | 20-3 | 23-5 | 29-1 | 34-0 | 38-6 | 51-8 | 69-7 | 106-8 |
| | 7-6 | 8-8 | 9-10 | 11-1 | 13-6 | 17-6 | 20-3 | 24-7 | 32-8 | 41-9 | 64-0 | 94-0 | 137-6 | 1600 | 500 | 200 |
| $f8$ | 6-5 $\frac{1}{2}$ | 7-3 $\frac{1}{2}$ | 8-1 $\frac{1}{2}$ | 8-11 | 10-6 | 12-8 $\frac{1}{2}$ | 14-1 $\frac{1}{2}$ | 16-2 | 19-3 | 22-1 | 27-0 | 31-3 | 35-0 | 45-6 | 58-9 | 83-4 |
| | 7-7 $\frac{1}{2}$ | 8-10 | 10-1 | 11-4 $\frac{1}{2}$ | 14-0 | 18-3 | 21-4 | 26-4 | 35-9 | 46-10 | 77-0 | 125-0 | 214-2 | 500 | 200 | 500 |
| $f11$ | 6-3 $\frac{1}{2}$ | 7-0 $\frac{1}{2}$ | 7-10 | 8-7 | 10-0 | 12-0 | 13-3 | 15-0 | 17-8 | 20-1 | 24-1 | 27-4 | 30-7 | 37-8 | 46-6 | 60-6 |
| | 7-8 | 8-9 | 9-10 | 10-11 | 12-15 | 15-17 | 17-20 | 20-25 | 25-30 | 30-40 | 40-50 | 50-60 | 60-70 | 100-100 | 200-200 | 500-800 |
| | 7-11 | 9-2 $\frac{1}{2}$ | 10-7 | 12-0 | 15-0 | 20-0 | 23-8 | 29-10 | 42-8 | 59-6 | 118-0 | 288-0 | 500 | 500 | 500 | 500 |
| $f16$ | 6-0 | 6-8 $\frac{1}{2}$ | 7-5 | 8-0 $\frac{1}{2}$ | 9-4 | 11-0 | 12-1 | 13-6 | 15-8 | 17-5 | 20-5 | 22-9 | 24-7 | 29-5 | 34-6 | 41-8 |
| | 7-8 | 8-9 | 9-10 | 10-11 | 12-15 | 15-17 | 17-20 | 20-25 | 25-30 | 30-40 | 40-50 | 50-60 | 60-70 | 100-100 | 200-200 | 500-800 |
| | 8-5 | 9-11 | 11-6 | 13-2 | 16-10 | 23-5 | 28-8 | 38-5 | 62-6 | 107-0 | 1000 | 500 | 500 | 500 | 500 | 500 |
| $f22$ | 5-8 | 6-4 | 6-11 $\frac{1}{2}$ | 7-6 | 8-7 | 10-0 | 10-11 | 12-0 | 13-8 | 15-1 | 17-3 | 18-10 | 20-2 | 23-3 | 26-4 | 30-3 |
| | 7-8 | 8-9 | 9-10 | 10-11 | 12-15 | 15-17 | 17-20 | 20-25 | 25-30 | 30-40 | 40-50 | 50-60 | 60-70 | 100-100 | 200-200 | 500-800 |
| | 9-1 $\frac{1}{2}$ | 10-10 $\frac{1}{2}$ | 12-0 | 14-11 | 19-11 | 29-9 | 38-10 | 59-0 | 144-0 | 500 | 500 | 500 | 500 | 500 | 500 | 500 |
| $f32$ | 4-8 | 5-9 $\frac{1}{2}$ | 6-3 $\frac{1}{2}$ | 6-9 | 7-7 $\frac{1}{2}$ | 8-8 $\frac{1}{2}$ | 9-4 | 10-2 | 11-4 $\frac{1}{2}$ | 12-3 $\frac{1}{2}$ | 13-8 | 14-8 $\frac{1}{2}$ | 15- $\frac{1}{2}$ | 17-3 | 18-10 | 20-10 |
| | 7-8 | 8-9 | 9-10 | 10-11 | 12-15 | 15-17 | 17-20 | 20-25 | 25-30 | 30-40 | 40-50 | 50-60 | 60-70 | 100-100 | 200-200 | 500-800 |
| | 10-6 | 13-0 | 15-10 | 19-3 | 28-4 | 53-6 | 91-6 | 500-0 | 500 | 500 | 500 | 500 | 500 | 500 | 500 | 500 |

XX.—DEPTH OF FIELD FOR LENSES OF 10 INCH (250 mm.) FOCAL LENGTH

| | | | | | | | | | | | | | | | | |
|-------|--------------------|--------------------|---------------------|--------------------|--------------------|---------------------|---------------------|--------------------|-------|-------|-------|-------|-------|-------|-------|-------|
| f 2 | 6.10 $\frac{1}{2}$ | 7-10 | 8-9 $\frac{1}{2}$ | 9-9 | 11-8 | 14-6 | 16-4 | 19-1 | 23-7 | 28-0 | 36-6 | 44-8 | 52-6 | 82-4 | 135-0 | 416-8 |
| | 7-1 $\frac{1}{2}$ | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 40 | 50 | 60 | 100 | 200 | OO |
| | 7-1 $\frac{1}{2}$ | 8-2 $\frac{1}{2}$ | 9-2 $\frac{1}{2}$ | 10-3 | 12-4 | 15-6 $\frac{1}{2}$ | 17-9 | 21-0 | 26-7 | 32-4 | 44-3 | 56-9 | 70-0 | 131-6 | 384-0 | OO |
| f 2.5 | 6.10 $\frac{1}{2}$ | 7-9 $\frac{1}{2}$ | 8-9 | 9-8 $\frac{1}{2}$ | 11-7 | 14-4 | 16-2 | 18-10 | 23-3 | 27-6 | 35-9 | 43-6 | 51-0 | 77-0 | 125-0 | 333-4 |
| | 7-2 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 40 | 50 | 60 | 100 | 200 | OO |
| | 7-2 | 8-2 $\frac{1}{2}$ | 9-3 | 10-3 $\frac{1}{2}$ | 12-5 $\frac{1}{2}$ | 15-8 $\frac{1}{2}$ | 17-11 | 21-3 | 27-1 | 33-0 | 45-6 | 58-10 | 73-3 | 143-0 | 500-0 | OO |
| f 3 | 6.10 | 7-9 $\frac{1}{2}$ | 8-8 $\frac{1}{2}$ | 9-8 | 11-6 | 14-3 | 16-0 | 18-8 | 22-11 | 27-1 | 35-0 | 42-4 | 49-4 | 73-6 | 116-6 | 277-9 |
| | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 40 | 50 | 60 | 100 | 200 | OO |
| | 7-2 $\frac{1}{2}$ | 8-2 $\frac{1}{2}$ | 9-3 $\frac{1}{2}$ | 10-4 $\frac{1}{2}$ | 12-6 $\frac{1}{2}$ | 15-10 | 18-1 $\frac{1}{2}$ | 21-6 $\frac{1}{2}$ | 27-6 | 33-8 | 46-9 | 61-0 | 76-8 | 156-0 | 714-0 | OO |
| f 3. | 6-9 $\frac{1}{2}$ | 7-9 | 8-8 | 9-7 | 11-5 | 14-1 | 15-10 | 18-6 | 22-7 | 26-8 | 34-3 | 41-4 | 48-0 | 70-6 | 109-0 | 238-3 |
| | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 40 | 50 | 60 | 100 | 200 | OO |
| | 7-2 $\frac{1}{2}$ | 8-3 $\frac{1}{2}$ | 9-4 | 10-5 | 12-7 $\frac{1}{2}$ | 16-0 | 18-4 | 21-10 | 27-11 | 34-4 | 48-0 | 63-4 | 80-3 | 172-0 | 1234 | OO |
| f 4 | 6-9 $\frac{1}{2}$ | 7-8 $\frac{1}{2}$ | 8-7 $\frac{1}{2}$ | 9-6 $\frac{1}{2}$ | 11-4 | 14-0 | 15-8 $\frac{1}{2}$ | 18-3 | 22-4 | 26-3 | 33-6 | 40-3 | 46-8 | 67-3 | 102-0 | 208-6 |
| | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 40 | 50 | 60 | 100 | 200 | OO |
| | 7-3 | 8-4 | 9-5 | 10-6 | 12-9 | 16-2 | 18-6 | 22-2 | 28-5 | 35-1 | 49-6 | 65-10 | 84-2 | 192-6 | 5000 | OO |
| f 4.5 | 6-9 | 7-8 | 8-7 | 9-6 | 11-3 $\frac{1}{2}$ | 13-10 $\frac{1}{2}$ | 15-7 | 18-0 | 22-0 | 25-10 | 32-11 | 39-4 | 45-4 | 65-0 | 96-0 | 185-3 |
| | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 40 | 50 | 60 | 100 | 200 | OO |
| | 7-3 $\frac{1}{2}$ | 8-4 $\frac{1}{2}$ | 9-5 $\frac{1}{2}$ | 10-7 | 12-10 | 16-4 | 18-8 $\frac{1}{2}$ | 22-5 | 28-10 | 35-10 | 51-2 | 68-6 | 88-9 | 217-6 | OO | OO |
| f 5.6 | 6-8 $\frac{1}{2}$ | 7-7 | 8-6 | 9-4 $\frac{1}{2}$ | 11-1 $\frac{1}{2}$ | 13-7 $\frac{1}{2}$ | 15-3 | 17-8 | 21-5 | 25-0 | 31-6 | 37-6 | 42-9 | 60-0 | 85-5 | 149-0 |
| | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 40 | 50 | 60 | 100 | 200 | OO |
| | 7-4 | 8-5 $\frac{1}{2}$ | 9-7 | 10-8 $\frac{1}{2}$ | 13-0 $\frac{1}{2}$ | 16-8 | 19-2 | 23-1 | 30-0 | 37-7 | 54-7 | 75-3 | 100-0 | 304-0 | OO | OO |
| f 6.3 | 6-8 | 7-6 $\frac{1}{2}$ | 8-5 | 9-3 $\frac{1}{2}$ | 11-0 | 13-6 | 15-1 | 17-5 | 21-0 | 24-6 | 30-9 | 36-4 | 41-5 | 57-2 | 80-0 | 133-4 |
| | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 40 | 50 | 60 | 100 | 200 | OO |
| | 7-4 $\frac{1}{2}$ | 8-6 | 9-8 | 10-10 | 13-2 | 16-11 | 19-6 | 23-6 | 30-9 | 38-9 | 57-0 | 80-0 | 109-0 | 400-0 | OO | OO |
| f 8 | 6-6 $\frac{1}{2}$ | 7-5 $\frac{1}{2}$ | 8-3 $\frac{1}{2}$ | 9-1 $\frac{1}{2}$ | 10-9 | 13-1 | 14-7 | 16-9 | 20-2 | 23-4 | 29-0 | 33-10 | 38-0 | 51-0 | 68-6 | 104-3 |
| | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 40 | 50 | 60 | 100 | 200 | OO |
| | 7-6 | 8-8 | 9-10 $\frac{1}{2}$ | 11-0 $\frac{1}{2}$ | 13-7 | 17-6 | 20-4 | 24-9 | 33-0 | 42-2 | 65-0 | 96-3 | 141-6 | 2500 | OO | OO |
| f 11 | 6-5 | 7-3 | 8-0 $\frac{1}{2}$ | 8-10 | 10-4 $\frac{1}{2}$ | 12-6 | 13-10 $\frac{1}{2}$ | 15-10 | 18-10 | 21-6 | 26-2 | 30-1 | 33-6 | 43-0 | 55-0 | 75-8 |
| | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 40 | 50 | 60 | 100 | 200 | OO |
| | 7-8 $\frac{1}{2}$ | 8-11 $\frac{1}{2}$ | 10-2 $\frac{1}{2}$ | 11-6 $\frac{1}{2}$ | 14-3 | 18-5 | 21-11 | 27-2 | 37-4 | 49-8 | 84-8 | 147-0 | 283-4 | OO | OO | OO |
| f 16 | 6-2 | 6-11 $\frac{1}{2}$ | 7-8 | 8-4 $\frac{1}{2}$ | 9-9 | 11-8 | 12-10 | 14-5 $\frac{1}{2}$ | 16-11 | 19-0 | 22-7 | 25-6 | 27-10 | 34-3 | 41-4 | 52-7 |
| | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 40 | 50 | 60 | 100 | 200 | OO |
| | 8-1 | 9-5 $\frac{1}{2}$ | 10-10 $\frac{1}{2}$ | 12-4 $\frac{1}{2}$ | 15-7 | 21-1 | 25-3 | 32-6 | 48-0 | 71-0 | 172-6 | 1250 | OO | OO | OO | OO |
| f 22 | 5-11 | 6-7 $\frac{1}{2}$ | 7-3 $\frac{1}{2}$ | 7-11 | 9-11 $\frac{1}{2}$ | 10-9 | 11-9 | 13-1 | 15-1 | 16-9 | 19-5 | 21-6 | 23-2 | 27-6 | 31-10 | 37-10 |
| | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 40 | 50 | 60 | 100 | 200 | OO |
| | 8-7 | 10-2 | 11-10 | 13-7 | 17-7 | 24-10 | 30-13 | 42-6 | 73-9 | 145-0 | OO | OO | OO | OO | OO | OO |
| f 32 | 5-6 $\frac{1}{2}$ | 6-11 $\frac{1}{2}$ | 6-8 $\frac{1}{2}$ | 7-2 $\frac{1}{2}$ | 8-2 $\frac{1}{2}$ | 9-6 | 10-3 | 11-4 | 12-9 | 13-11 | 15-9 | 17-1 | 18-2 | 20-8 | 23-0 | 26-4 |
| | 7 | 8 | 9 | 10 | 12 | 15 | 17 | 20 | 25 | 30 | 40 | 50 | 60 | 100 | 200 | OO |
| | 9-7 | 11-6 $\frac{1}{2}$ | 13-9 | 16-3 | 22-4 | 35-6 | 49-0 | 86-8 | 650-0 | OO | OO | OO | OO | OO | OO | OO |

THE DEFECTS IN EVERY LENS

Aberrations

Practically all lenses now available are distinctly imperfect from the critical point of view of the designer.

The same lenses are often of excellent quality by the standards of the man who uses them. Many a photographer thinks that he has a really fine lens, and is proud of the results it gives, until quite suddenly it lets him down on a job where absolutely first class work is needed, and he realises that the standard by which the lens was judged was not high enough.

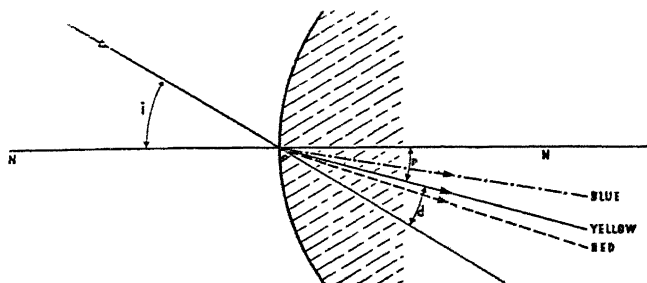
It cannot be too strongly stressed that the best and most up-to-date of modern lenses are not free from faults in their performance, or aberrations as they are called. Catalogues and patent specifications claim that aberrations are eliminated, but this is only part of the truth. The plain fact is that all aberrations, or even a good percentage of them, cannot be and are not eliminated. Among designers and specialists on lens work, these claims are accepted as only a conventional way of saying that some troublesome aberrations have been reduced to within reasonable limits, that others have been nicely balanced, and that a workman-like job has been made of the complete lens.

To have a really good and exact idea of what a lens can be expected to do means getting some insight into the exact way in which a lens produces an image, into the type of faults that may arise, and where it is a question of taste in balancing aberrations.

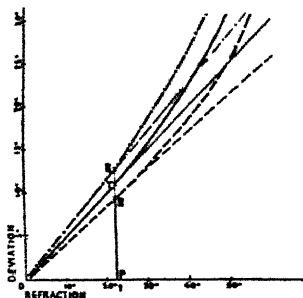
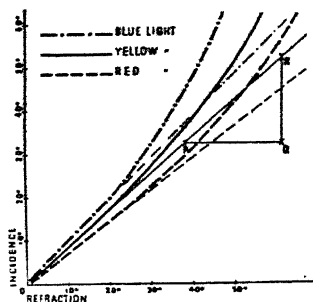
And of these the first is to see exactly how the lens bends the rays of light to form an image.

Refraction of Light

Whenever a ray of light crosses a surface separating glass and air it suffers an abrupt bending or refraction, as shown on p. 95. The angle that the ray makes with the line ON, at



A ray of white light is bent by glass and split up into rays of its component colours. The angle that the incoming ray makes with the line at right angles to the element of surface that the ray hits, is the *angle of incidence*. The angle that the ray makes with the same line after it is bent is the *angle of refraction*, and the angle between the directions of the ray before and after bending is the *angle of deviation* (p. 96).



The relations between the angle of incidence i , the angle of refraction r and the angle of deviation d are shown in the graphs for light of different colours. $RQ \div PQ$ is the *index of refraction*. $PY \div BR$ is the *Abbe number*. The index of refraction, which varies from colour to colour since light of different colours is bent to different extents by the same piece of glass, measures the power of the glass to bend light rays. The Abbe number measures the difference in bending power for light of different colours. The greater the Abbe number the smaller the *dispersion* or the amounts by which light of different colours is differently bent (p. 97).

THE REFRACTION OF LIGHT

right angles to the surface, is the "angle of incidence." The angle that it makes with the same line ON after it has been refracted at the surface is the "angle of refraction." The amount of bending that the ray undergoes, the amount by which it deviates after refraction from the direction it pursues before hitting the surface, is the "angle of deviation," or merely the "deviation," and is shown on p. 95.

The best way of showing the amount of bending that a ray of light undergoes for varying angles of incidence is to draw two graphs dealing with different aspects of the bending. In the first graph, on p. 95, the angle of incidence is plotted on the vertical line and the angle of refraction is plotted along the horizontal axis. The graph shows how the two are connected. In the second graph on p. 95 the angle of deviation is plotted on the vertical line against the angle of refraction on the horizontal.

In the graph on p. 95, it will be seen that the first part of the curve is very nearly a straight line. A point moving along the curve connecting the angles of incidence and refraction starts off moving along the line OPR . Once the slope of the line OPR is known the rest of the curve follows in a perfectly definite way, and is obtained by purely mathematical calculation. Because of this the behaviour of the glass in bending light can be described by giving the slope or gradient of the line OPR .

The slope of the line OPR , i.e., the height QR that a point on the line rises when it travels a distance PQ equal to one unit in the horizontal direction, is called the "refractive index" of the glass, and measures the bending power of the glass.

Dispersion

The bending power of the glass is not the same for all colours of light. A ray of blue light is bent more strongly than a ray of yellow light, and this in turn is bent more strongly than a ray of red light. This is shown on p. 95 where the unbroken line in the glass represents the path taken by a ray of yellow light incident on the surface as

shown; the dotted line shows the path taken by a ray of blue light that coincides with the direction of the yellow ray before either of them strike the glass surface, and the chained line shows the same thing for a ray of red light. This means that when graphs are drawn as on p. 95, and the curves relating to different colours lie apart from one another, as shown in detail on p. 95, where the dotted line again refers to rays of blue light and the chained line to rays of red light. The slopes of the three curves and the straight lines with which they coincide in their early stages are different for the three colours mentioned. In other words the glass has a distinctive refractive index for each colour of light.

When the refractive index of a glass is mentioned without any statement of the colour of light used it can be assumed quite safely that the index has been measured for yellow light, and it will be assumed throughout this chapter that unless a special mention is made the index of refraction is that for yellow light.

The fact that glass bends light of different colours to different extents is the "dispersion" of the glass.

The graph on p. 95 comes in very useful in forming an estimate of the dispersion of the glass, and in measuring its dispersive power. Suppose that the straight lines from the early parts of the curves for blue light, yellow light, and red light, cut a vertical line drawn through the point *P*, in the points *B*, *Y*, and *R*, as shown on p. 95. *PY* gives an estimate of the deviating power of the glass as far as yellow light is concerned. The same thing holds for *PB* and *PR* for blue and red light. *BR* gives an estimate of the difference of deviating power as the colour of the light changes from blue to red. The dispersive power is then measured by giving the Abbe number of the glass, usually denoted by *V*, where

$$V = \text{length of } PY \div \text{length of } BR.$$

When the refractive index of a glass is given, and its Abbe number also, it is specified sufficiently clearly for most optical purposes.

The exact value of the refractive index and Abbe number of a glass depends on the constituents of the glass. By using different materials glasses of very many types can be made.

XXI.—REFRACTIVE INDEX AND ABBE NUMBER OF GLASSES

| Glass Type | Index of Refraction | Abbe Number |
|---------------------------------|---------------------|-------------|
| Hard Crown | 1.518 | 60.3 |
| Borosilicate Crown | 1.509 | 64.4 |
| Medium Barium Crown | 1.576 | 57.4 |
| Dense Barium Crown... .. | 1.613 | 60.0 |
| Light Flint | 1.583 | 41.8 |
| Dense Flint | 1.621 | 36.1 |
| Extra Dense Flint | 1.652 | 33.6 |
| Double Extra Dense Flint | 1.802 | 25.5 |

For instance, in the case of Hard Crown glass, which has very nearly the same properties as ordinary plate glass, the index of 1.518 means that the slope of the straight line *OPR* on p. 95, is 1.518, the line is rising upwards at 1.518 times the rate at which it is travelling horizontally ; and the Abbe number of 60.3 means that on p. 95 the length of *PY* is 60.3 times the length of *BR*. (It does not matter where the vertical through *BR* is drawn. A new position merely scales up the lengths. The ratio of *PY* to *BR* stays the same).

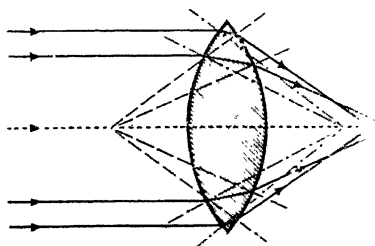
All the glasses mentioned above, and many more, find their place in giving a good lens a high standard of performance.

Until recently the basic material of all optical glasses was silica—a very pure form of sand. There a high refractive index implied a low Abbe number. By the introduction of other rather expensive materials new glasses have been made which contain very little silica, and in which high Abbe numbers are associated with high refractive indices.

The Path of Light in a Lens

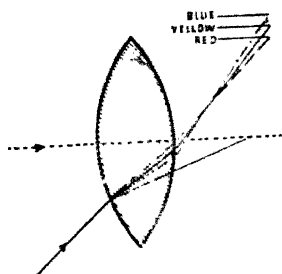
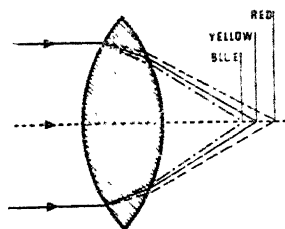
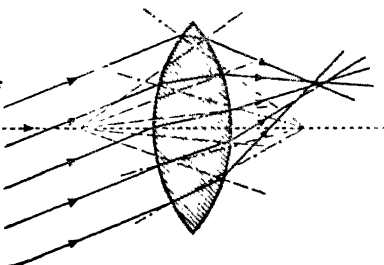
The paths of two rays of light through a simple lens are shown on p. 99.

Each ray as it enters the glass is bent towards the line at right angles to the bit of the surface where it hits the glass. The area very near to each of these points can be considered



Left : The laws governing the bending of light by glass mean that the rays bent by a simple lens do not meet again in the point required of a perfect lens (p. 100).

Right : When the rays of light incident on the lens make an angle with the lens axis the bending of light according to the laws already described results in a light patch being formed of a decidedly complicated form (p. 100).



Left : Blue light is bent more strongly than yellow and red light and so the blue rays cut the axis nearest the lens.

Right : In general a simple lens breaks up an oblique ray into a group of coloured rays which give a tiny spectrum on a focusing screen.

REFRACTION BY A LENS

as flat and so there is no difficulty in drawing a line at right angles to the localised position of these portions of the surface. The relation between the angle in air and in the glass is given by the graphs on p. 95.

When each ray leaves the surface it is bent away from the line at right angles to the surface, but the relations between the angles in air and in the glass are the same as before. The net result of these two bendings is shown on p. 99.

The main thing to notice is that the rays do not come to a sharp focus after they leave the lens. They cut the axis in different points, and the best that they can do in the way of forming an image, when all the rays that go through the lens are taken into account, is a disc of light on a sensitive plate or focusing screen.

When the rays come from a point away from the lens axis exactly the same type of thing is found, but in an aggravated form and the light patch produced on the plate is of a more complicated shape. The paths of the rays in this case are shown on p. 99.

And in addition to this there is the complication introduced by the varying extents to which light of different colours is bent by the glass. The effects of this for one of the rays is shown on p. 99. A ray of white light, containing in itself rays of red, orange and other colours, throughout the range of the spectrum, is shown hitting a single lens. The differing extents to which light of different colours is bent by the glass means that the single ray of white light is split up into a group of rays as soon as it crosses the first surface. This is shown on p. 99. The red and blue rays are shown flanking the yellow ray. When the rays cross the second surface this divergence between the different colours is emphasised, and the rays cut the lens axis in different points.

As far as images are produced by such a lens they are found at varying distances from the lens, depending on their colour. The blue image is nearest the lens, the greenish-blue next, followed by the green, the yellow, and so on down to the red image which is farthest away.

When the initial ray comes from a point away from the lens axis there is another quite different colour effect, as shown on p. 99, where blue, yellow and red rays are drawn. The rays, derived from an initial white ray, when they leave the lens cut any plate in different points. In place of forming a clear cut image point, each ray of white light produces a tiny spectrum on the plate or focusing screen.

These colour effects are, of course, superimposed on the effects already mentioned whereby a light patch is produced instead of an image point.

The Perfect Lens Again

It is only by courtesy that such a piece of glass can be called a lens. The definition it gives is hopeless. But its performance can be improved by stopping it down and using a filter (page 273) that cuts off all except a very narrow band of colours. As the lens aperture is decreased, and the colour band restricted in width by the filter, there is a progressive improvement in the definition afforded by the lens. The limit that the lens is aiming at as these restrictions on aperture and range of colour transmitted are tightened up, and the goal which it never attains, is that of a perfect lens. But, at the same time, to ensure this result, the field of the lens, the size of the plate it covers, must be cut down drastically to a quite infinitesimal area.

It is on the basis of this goal of the lens performance under severe restrictions that all calculations on lens performance, such as those concerned with focal points and nodal points, are made.

Any lens when stopped down far enough, when used over a severely restricted field, and restricted to one colour of light, tends to behave as a perfect lens. (There is one feature of the way in which light travels and spreads, namely diffraction, that enters into the picture at very low lens apertures, and that tends to vitiate what has been said above. But for the present diffraction can safely be left out of things. A description of what it is and how it introduces a new factor

into the performance of a lens is given later on page 137. It is out of place to discuss it at this stage.)

As the lens aperture and field, and colour range are opened out from the quite impractical values needed to give the lens a semblance of being a perfect lens, flaws in the performance begin to appear, the so-called "aberrations."

Higher-order Aberrations

The first aberrations to appear are the *first-order aberrations*. They are the only aberrations of any importance at lens apertures and fields below about $f/16$ and 10 degrees respectively. They are often called the *Seidel aberrations*, after the German mathematician of that name, who was concerned with developing methods of working out their values, although the defects themselves had been known at an earlier date to English opticians such as *Coddington* and *Airy*.

Even at the limits of field and aperture where the first-order aberrations are the dominating faults in the lens, there are traces of other aberrations. These appear in appreciable amounts as either the lens aperture or lens field, or both are opened out beyond the values to which they must be restricted if only the first-order aberrations are to be taken into account. They are usually just lumped together as the *higher-order aberrations*. It is possible to sort them out into various groups, and to call these second-order, third-order aberrations and so on, but this sorting out is not worth while as a rule.

Many accounts of lens aberrations have limited themselves to the first-order aberrations, which are, after all, the simplest to describe and deal with. But it is really the higher-order aberrations that in many cases ruin a lens performance. It is a comparatively simple matter, especially with the most recent types of glass, to correct a lens for all the first-order aberrations. When that is done, however, the second and higher-order aberrations come into play strongly and steps have to be taken to correct these new defects. These same

steps that are taken to eliminate the higher-order aberrations, as far as this is possible, lead to the re-introduction of the first-order aberrations.

The whole art and science of producing a new lens consists in balancing the first and higher-order aberrations with a minimum amount of each. None of them are entirely eliminated. It is these residual amounts of aberration that determine the quality of a lens performance, and the next thing to do is to give a short account of what they are and the results they produce.

The aberrations can best be described as belonging to five different types, each having its own characteristic contribution to the quality of the negative produced by the lens. They are

- (1) Spherical Aberration
- (2) Coma
- (3) Astigmatism and Field Curvature
- (4) Distortion
- (5) Chromatic effects,

and are dealt with in this order.

Spherical Aberration

Whatever else a lens may be expected to do, it is expected except in the case of an avowedly soft-focus portrait lens (p. 179), to give a really crisp and sharp image in the centre of the negative. Whether this result is achieved or not depends on the amount of spherical aberration in the lens.

And whether the focus of the lens changes or not as it is stopped down, depends as far as central definition is concerned, i.e., definition in the centre of the negative, on the amount of spherical aberration.

On p. 105 rays of light parallel to the lens axis are shown as they are bent by a simple converging lens. Next are shown the same rays as they are bent by a simple diverging lens. The fact to note is that in each case the rays that pass through the margins of the lenses converge to, or diverge from, points nearer to the lens than do the rays from more central

parts of the lenses. In each case the marginal rays are bent more strongly than the rays through the more central parts of the lens.

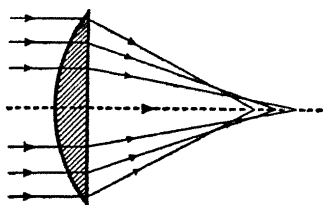
This feature of the performance of any lens, namely that rays of light (of one particular colour) initially parallel to the lens axis, are bent by the lens so that the rays from the margin of the lens cut the axis in points other than those in which it is cut by rays from inner zones, is the "spherical aberration" of the lens.

Using the fundamental laws of refraction discussed in the early part of this chapter, it is a simple matter to prove mathematically that if the polished surfaces of a single lens are spherical in shape, then all the rays passing through the lens from a point object cannot converge to a single point image. Hence, the name spherical aberration. This aberration can, however, be completely absent in single lenses whose surfaces are not spherical. Photographic lens surfaces have to be made to a very high accuracy of shape, an accuracy measured in terms of a few millionths of an inch. Since the desired precision is only possible, economically, on spherical surfaces, it follows that spherical aberration is an important limitation on lens performance.

When the rays are bent by a lens so that the rays from the margin of the lens cut the axis nearer to the lens than those from inner zones, as shown for a simple lens on p. 105, then the lens has *under-corrected* spherical aberration.

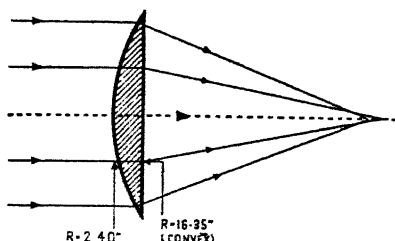
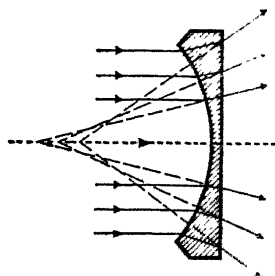
A simple lens always has under-corrected spherical aberration. The exact amount, for a lens of a given focus, depends on the shape of the lens. With a single lens of crown glass with a refractive index of 1.52 the minimum amount of spherical aberration is obtained when the shape of the lens is as shown on p. 105, which shows a lens of 4 inch focus.

A simple diverging lens, as illustrated on p. 105, always tends to make the rays of light through the marginal parts diverge away from the axis to a greater extent than rays through the more central zones, as also shown on p. 10.5 The excessive divergence of the marginal rays depends on the shape of the lens, on the ratios of the curvatures of its two surfaces, in exactly the same way that the excessive



Left : With a simple converging lens the rays farthest from the axis converge too strongly, and cut the axis nearest to the lens (p. 104).

Right: The rays bent by the marginal parts of a diverging lens appear to come from points nearer the lens than those from inner zones (p. 104).



Above : By a suitable choice of lens shape the excessive convergence of marginal rays can be reduced to a minimum. The form of a 4 inch lens is shown which has minimum spherical aberration for one particular type of glass. The under-correction of spherical aberration cannot be removed by the use of a single glass, but merely brought to a minimum by a judicious choice of curve radii. The example shown is for a lens made of hard-crown glass with a refractive index of 1.520 (p. 104).

SPHERICAL ABERRATION OF SIMPLE LENSES

convergence of the marginal rays in a converging lens depends on the shape of the lens.

The most important result of this is that a converging lens can be combined with a diverging lens of lesser power, so that the combination of the two lenses is converging, and by a proper choice of the shape of the diverging lens the excessive convergence and divergence of the two lenses can be balanced. In the combination of the two lenses the marginal rays through the pair are brought to the same focus as the rays through the innermost zones of the lens.

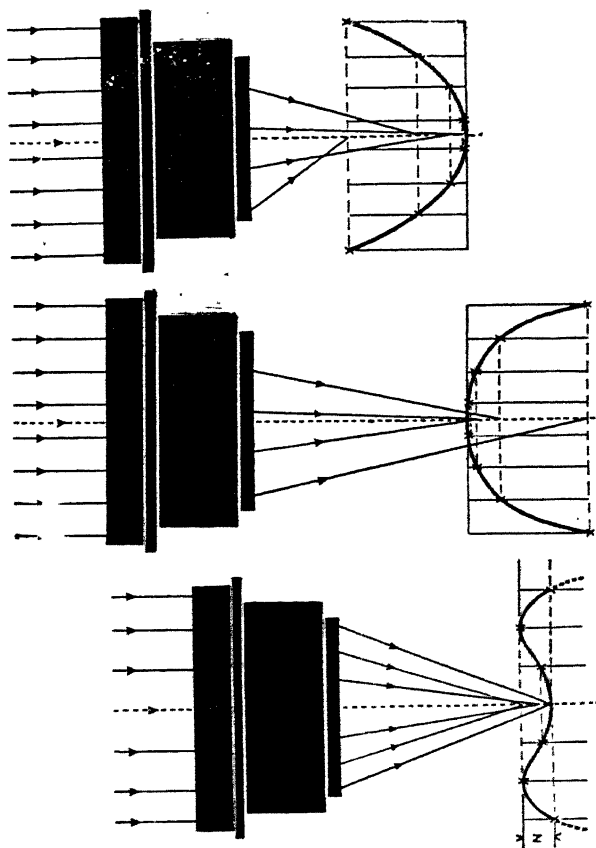
By a suitable choice of the shape of the negative lens the rays through the margin of the compound lens can be made to come to a focus farther away from the lens than those through the innermost zones. In this case the lens has *over-corrected* spherical aberration.

In any lens, whether it is of the simple form of a compound lens, as just described, or whether it is of a more complicated construction, such as is described on pages 141 ff, the description of spherical aberration remains the same: if rays through the margin of the lens come to a shorter focus than rays through the innermost zones of the lens, the lens has *under-corrected* spherical aberration; if they come to a longer focus the lens has *over-corrected* spherical aberration.

Zonal Aberration

When a lens is of a more complicated construction than a simple compound lens, the same general method of using one or more negative lenses of the proper shape, means that rays of light through the edge of the full lens aperture can be brought to the same focus as rays through the innermost zones of the lens aperture. In this case it is possible to say that the spherical aberration has been corrected, but this cannot be taken as indicating that the lens will give good central definition. It may still happen that the definition in the centre of the film or plate is just hopeless.

Because of the importance of having a really sharp



Top : The effect of first order under correct-spherical aberration is to make rays from zones of the lens come to progressively shorter foci as the zone diameters increase (p. 108).

Centre : Second order over-correct spherical aberration causes a progressive lengthening of the focus of rays from lens zones (p. 108).

Bottom : The case of practical importance when first and second order aberrations are present means a shortening of the focus to a minimum followed by progressive lengthening. It produces zonal aberration (p. 108).

THE CAUSE OF ZONAL SPHERICAL ABERRATION

definition in the centre of the plate it is worth while going into the subject in more detail.

The rays at the margin of the lens aperture are brought to the same focus as rays through the innermost zones, not because all the orders of spherical aberration have been removed, the first order, second order, and all the higher orders as explained on page 102, but because they have been balanced for the rays through the margin of the lens. The best way to see the results of this balancing is to deal with the effects of first order and second order spherical aberration separately, and then to combine the two.

Suppose that a lens suffers from first-order spherical aberration only, and has under-corrected spherical aberration only. Then all the rays through the lens show a progressive shortening of focus as their distance from the lens axis increases. This is shown on p. 107; the graph on the right of the figure measures off more clearly the shortening of focus for rays from a particular zone. The distance that a point on the graph is to the left of the vertical line shows how much the rays from a zone that height above the axis fall short of the focus of rays through the innermost zone.

Next, suppose that it suffers from second-order over-corrected spherical aberration only. The rays from different zones of the lens come to progressively longer foci as the distance of the zone from the lens axis increases. This is shown on p. 107, where again the graph at the right of the diagram shows the progressive lengthening of focus in a clearer way. The point to notice about the graph in this case is this : In its early stages it hugs the vertical line much more closely than does the curve for first-order spherical aberration, and in the later stages of its course it is leaving the vertical line at a much more rapid rate than the first-order curve. The diagrams have been drawn so that the sizes of the under and over-correction in the two cases are equal at the margin of the lens aperture.

And now take the type of thing that occurs in practice, where the lens has both aberrations at the same time.

At the edge of the lens aperture the under-correction

from the first-order just balances the over-correction from the second-order and the rays from this region of the lens aperture come to the same focus as the rays from the innermost zones of the aperture, as shown on p. 107.

In regions not too remote from the centre of the lens aperture, the first-order spherical aberration dominates anything else, and there is a progressive shortening of the focus of rays through succeeding zones. As these move out from the centre of the lens the second order aberration tends to slow up the rate at which this shortening takes place, and finally stops it. Beyond this point the second order aberration takes control and there is an increasingly rapid lengthening of focus until the margin of the lens aperture is reached. The whole behaviour is shown on p. 107.

This is the type of performance of every lens made. *The fact that the rays through an intermediate zone come to a shortest focus is referred to as the zonal spherical aberration of the lens. The zonal spherical aberration is of the greatest importance in determining the quality of the lens definition.*

In many cases the second and higher-order aberrations (only the second order was dealt with explicitly above but the higher-order spherical aberrations have exactly the same effect) are adjusted so that the rays through the extreme margin of the lens come to a slightly longer focus than the rays from the innermost zone of the lens aperture. This helps to move the position of shortest focus away from the lens, but it cannot be overdone without giving the lens poor definition through too much over-corrected spherical aberration.

Since the rays from each zone of the lens come to a different focus, on a plate or film each zone of the lens aperture gives a ring of light instead of a point of light. And from the whole lens aperture there is produced a disc of light. The size of this disc depends on the size of the zonal spherical aberration, and it should be realised that the zonal aberration cannot be eliminated. All that can be done is to try to reduce it to a reasonably small amount.

Enough has been said in this section to show that only a

conventional value can be put upon any claim that the spherical aberration in any lens has been corrected. All that such a statement implies is that there is not too much over-correction of spherical aberration at the margin of the lens aperture, nor too much zonal spherical aberration.

Whether the judgment of the maker as to what constitutes "too much" agrees with the judgment of the photographer can only be determined by actual test, notwithstanding any claims about the elimination of the aberration. More about the effects of spherical aberration and examining a lens for it is described in the less theoretical pages 224 ff. dealing with lens testing.

Coma

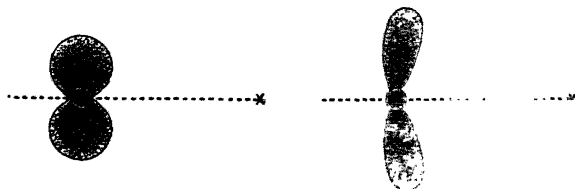
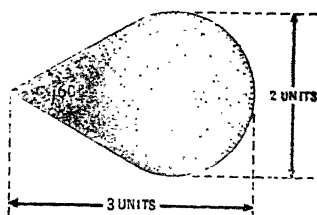
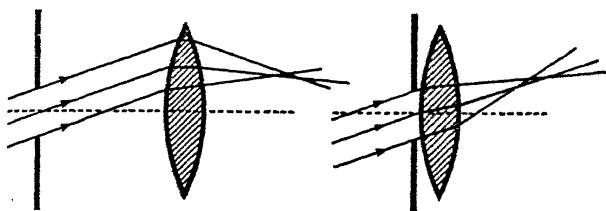
Suppose, although it is a thing that cannot be realised in practice, that the spherical aberration of a lens has been absolutely and completely corrected. It simplifies matters considerably in the following discussion to make this assumption, and then afterwards an allowance can be made for the fact that it is not an exact statement of the truth.

In just the same way all the other aberrations that afflict a lens and that cannot be completely eliminated, will be assumed to be absent, with the exception of coma.

Coma comes into play only when a point away from the lens axis is sending light to the lens. As far as central definition is concerned spherical aberration is the only aberration apart from chromatic aberrations (cf. pp. 122-126), that has any effect. Away from the centre of the negative other aberrations, of which coma is one, come into play and the stop has a new rôle to fulfil.

When the stop or iris diaphragm is used to cut down the diameter of a beam of light parallel to the lens axis, as explained at an earlier stage (on page 18), the same part of the lens is used no matter what the stop position may be, provided of course that the proper size stop is chosen in any position to give just the right diameter of beam.

But when a point off the lens axis is being dealt with the position of the stop fixes what part of the actual glass



Top : When the rays of light incident on a lens make an angle with the lens axis, and when they are cut off by a stop, the exact position of the stop determines what part of the lens is used by the rays of light that are allowed to pass. This has an important bearing on the type of aberration produced, especially in the case of coma (p. 110).

Centre : The shape of the light patch produced by first order coma is shown (p. 112).

Bottom : With higher orders of coma more complicated light patches are produced (p. 112).

COMA OF FIRST AND HIGHER ORDERS

surface is to be used. This is shown for the case of a simple lens on p. 111. The fact that a different part of the glass is used when the stop is in front of the lens, from that which is used when the stop is behind the lens means that the aberrations are different in the two cases, and that they depend on the position of the stop. This is of the utmost importance in establishing a lens construction that will give good definition, and holds whether the lens is of the simple construction shown or whether it is of a more complicated nature. Among other things this fact was responsible for the early vogue of the rapid-rectilinear and symmetrical type of lens (page 142).

When the lens is used to form an image of a point not far away from the axis and when the lens is closed down to a very small diameter, say $f/64$, the lens behaves sensibly as a perfect lens.

As the stop diameter is increased, to $f/16$ say, and the field increased to 4 or 5 degrees the light on the focusing screen is drawn out into a patch of light due to the operation of first-order coma. The shape of this patch is shown on p. 111, and while its absolute size varies from lens to lens its shape remains the same, and remains the same throughout the field as long as first order coma only need be taken into account. The light patch fades away in intensity from the head of the patch like the tail of a comet, hence the name. The coma tail may point away from the lens axis, in which case there is *outward coma*, or it may flare in from the head of the patch towards the lens axis, forming an *inward coma*.

As the lens aperture and field are opened out other orders of coma begin to appear and they are among the most troublesome things to deal with and to sort out from the aberrations. There is no such simplicity about them as about the first-order coma.

It is best just to say that the effect of higher orders of coma is to give an unsymmetrical flaring away of the patch of light on the plate or film. The coma tail as before may be either inwards towards the lens axis, or outwards away from the axis. The amount, and even the direction of the

major coma flare may vary over the field covered by the lens.

It is not easy to give examples of the type of appearance presented by the light patch of a lens afflicted with coma of various orders only, as in practically every case there is astigmatism (see below) also to contend with, and the two together, coma and astigmatism, produce particularly complicated light patches. The nearest approach in practice is probably the performance (of a wide-angle lens) of the type shown on p. 111, where there is illustrated the shape of the light patch at a few points in the field of the lens, and shows the type of coma balancing that has to be aimed at. In actual practice the coma correction at the margin of the field consists in making the curved figure-of-eight shown, more of a straight up and down figure-of-eight, but the example given shows the appearance that coma very easily takes in this case.

The really important cases are those in which both coma and astigmatism are concerned, and in which a more general definition of coma can be given. These are described in the next section after astigmatism has been discussed.

Astigmatism and Field Curvature

The characteristic effect of astigmatism is that one set of lines on a photographic plate is sharply in focus, and at the same time another set, at right angles to the first, is out of focus. When there is pure curvature of field both sets of lines are equally well in focus on a curved plate or film. The two things, astigmatism and curvature of field, are so intimately connected that it is best to deal with them at the same time.

To start with it will be taken for granted that all the aberrations with the exception of astigmatism and curvature of field are absent, and that the lens has been restricted both in aperture and field covered to small limits, say $f/16$ and 5 degrees respectively, although these are only very approximate figures to give something concrete to go by.

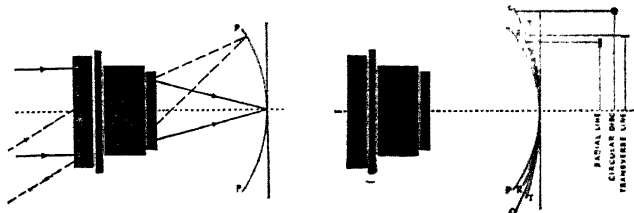
When there is only curvature of field in the lens a sharp image of a point in the field is formed, but in place of such

image points lying on a plane, the flat surface of a plate or film, they lie on a curved surface. Quite accurately enough they lie on the cap of a sphere, of which a section is shown on p. 115. The radius of this sphere depends only on the glasses of which the lens is made and their respective powers, and is given through a number called the *Petzval sum* of the lens. The greater the Petzval sum the more strongly curved is the cap of the sphere and the smaller its radius. With a normal type of anastigmat such as a symmetrical lens or *Cooke Triplet* (cf. page 160) the Petzval sum is positive and the spherical cap is concave to the lens as shown on p. 115. With some types of telephoto lens the Petzval sum is negative and the sphere is convex to the lens.

With the sharp image points lying on a curved surface the field of the lens is curved in the sense that the best definition would be obtained on a film bent to fit the spherical surface. If the Petzval sum of a lens is zero the sphere flattens out into a plane. It is rarely, if ever, a practical proposition to make the Petzval sum zero as other aberrations have also to be looked after, but a certain amount of flattening of the field of the lens can be carried out by a judicious use of astigmatism.

When there is astigmatism in the lens, as well as curvature of field, each object point in front of the lens has two images, one behind the other. Each of these images is a short straight line instead of a point, and the two lines are at right-angles to each other. The two lines are shown on p. 115. One points away from the lens axis, like a fragment of the spoke of a wheel : this is the sagittal or radial astigmatic line, or just the radial image. The other is at right angles to a line drawn from the lens axis, and is the tangential or transverse image.

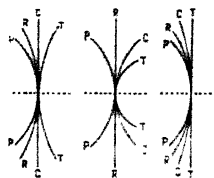
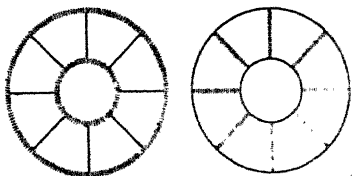
The relative positions of the radial and transverse images are also shown for one typical case on p. 115, and their varying positions for different positions of the object point in front of the lens are indicated by the curves that are cross-sections of image surfaces. When there is only curvature of field the sharp image points lie on the cap of a sphere



Top left : With pure field curvature image points lie on curved surface (P. 114).

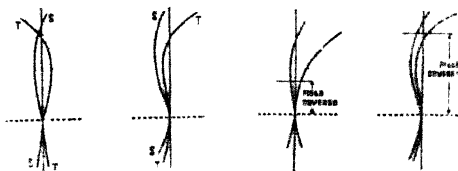
Top right : With astigmatism present there is a radial line on the surface R, a transverse line on the surface T, and between them a circular disc on the surface C. (p. 114).

Lower : By introducing varying amounts of astigmatism the R, T, C surfaces can be made to take the shapes shown (p. 116)



Above : If the radial astigmatic lines lie on a flat surface then the images of the spokes of a wheel are sharply defined but the rim of the wheel is poorly defined. If the transverse lines lie on a flat surface the rim of the wheel is sharply defined but the spokes are not (p. 116).

Right: The shapes of typical S and T surfaces when higher orders of astigmatism are present are shown, and the different shapes for narrow and medium angle lenses. In order to get the increased field required in some cases a compromise must be made in establishing the astigmatic correction, so that a lens designed for a comparatively large field will not give the same standard of performance near the centre of the field as one specifically designed to cover the smaller field (p. 117).



ASTIGMATISM

marked *PP* on p. 115. With astigmatism present the radial lines lie on the cap of the sphere marked *RR*, and the transverse lines on the cap of the sphere marked *TT* on p. 115. Midway between the spheres *RR* and *TT* of the radial and transverse image lines, the rays from the lens that converge to form these lines have a circular cross-section, as also shown on p. 115. For various positions of the object point the corresponding circular sections lie on the sphere marked *CC* on p. 115.

*By arranging the astigmatism in the lens suitably the surface *RR* and *TT* can be bent over to have the shape shown on p. 115, and in this case the circular sections or circular image discs lie on a flat surface.* The best all-round performance that a lens suffering from curvature of field can give is obtained when the astigmatism is adjusted so that the circular sections lie on a plane in which the sensitive film can be placed. The diameter of the disc obtained as the image in this case is only half the diameter of the out of focus disc that would have been obtained if a flat plate had been used with a lens suffering from pure curvature of field.

Other possibilities are shown on p. 115. The astigmatism can be adjusted so that either the radial or transverse image lines are made to lie on a flat surface.

When the radial lines lie on a flat surface then the edges of the image on the sensitive plate that stretch away from the lens axis are sharply defined, and the edges that stretch across the field, as shown on p. 115, are blurred. When the transverse lines lie on a flat surface the order of sharp definition and blurred definition is reversed, as also shown on p. 115.

In practice it is not possible to make the Petzval sum zero and to correct the astigmatism at the same time so that sharp image points are obtained on a flat surface. With a good quality lens of about $f/3$ aperture, with a focal length of 4 inches, the radius of the sphere given by the Petzval sum is about 10 inches.

When a lens of that focus has to cover only a small area, such as that of the 35 mm. cine-film frame, the usual astig-

matism correction is to arrange for the circular images to lie on a flat surface.

Higher Order Astigmatism

When the same lens has to cover the larger type of field required of it in still photography, i.e., to cover a plate with a diagonal of about 4 inches, there is another particularly important feature of the lens that has to be taken into account. This is the fact that while the radial and transverse image surfaces are spheres in the early parts of their careers, and are quite rapidly diverging from one another, in the later stages of their careers higher-order aberrations come into play and bend the two surfaces back again. Typical examples of such behaviour are shown on p. 115.

There are no simple rules giving the rate at which the two surfaces bend back. In any lens, to get the best possible average performance over the field covered, the astigmatism and curvature of field have to be adjusted so that the radial and transverse image surfaces deviate as little as possible from the plane of the sensitive film. Even in the best lenses this deviation is by no means negligible, and with a 4 inch focus lens, covering a plate with a diagonal of 4 inches, and having the radial and transverse surfaces as shown on p. 115, the surfaces may each deviate from the plane of the film or plate by .02 inches, and give a pronounced falling off in image quality.

Because of this behaviour of astigmatism in a lens it is always advisable to use the lens designed for the plate size of the camera employed. If the lens has been designed for a smaller field then the marginal definition will suffer considerably, especially owing to the tendency of the transverse image surface to go racing away, as shown on p. 115. If the lens has been designed for a larger field, then some quality of definition is lost because the astigmatism has been adjusted so that there will be no severe falling off in definition at the edge of the larger field, and a sacrifice of definition in the intermediate regions has to be made to ensure this result. On p. 115 are given diagrams showing the typical image

surfaces for a lens designed to cover various sizes of field. These emphasise the need for choosing the lens carefully to cover just the field for which it was designed.

Coma Plus Astigmatism

All that has been said above relates to the case where the lens aperture has been restricted to about $f/16$, and in the absence of coma. It still remains substantially true when the aperture is widened out to large apertures and when there is coma present, balanced in the way explained in the previous section.

What is then formed on the plate or film, as the image of an object point in front of the lens, is a patch of light with a hard core and a fringe of light balanced about this core. The fringe of light is the "coma fringe." Some typical examples are shown on p. 121.

The type of definition remains the same as that described above.

Suppose that attention is concentrated on a particular object point in front of the lens, away from the lens axis, and the light patch on a focusing screen that serves as its image when the lens suffers from astigmatism and coma. As the focusing screen moves away from the lens the shape of the light patch changes. A position is reached when a short line stretching away from the axis surrounded by a balanced and faint halo constitutes the light patch. In this position a short straight line through the object point, stretching away from the lens axis, would be reproduced with the best definition that the lens can afford. It is not sharply defined as far as perfect definition is concerned: it is of finite but small width, and accompanied by a halo that is very often only seen on an over-exposed photograph. If the focusing screen is moved either nearer to or further from the lens the definition of this fragment of a straight line falls off.

As the plate or focusing screen moves away from the lens still further a position is reached when radial and transverse

lines are equally ill-defined. Beyond that a point is reached when transverse lines have their best-defined images.

Even for one of the much vaunted miniature lenses, say a 2 inch $f2$ lens, covering 24×36 mm. film, the separation between the positions of the sharpest definition of radial and transverse lines may be .010 inch to .015 inch with consequent effects upon the quality of the definition away from the centre of the field, or the centre of the negative.

Field Performance

If the attention is directed to the images produced on a plate focused to get the sharpest central definition the type of performance is this: the definition is best in the centre of the negative. Then it falls off as the image patch moves away from the centre. Radial and transverse lines may not be equally ill-defined. The definition usually reaches a certain minimum of quality and then picks up, so that it is quite good just before the edge of the field, and then falls off again rapidly after this point.

There are many variants on this type of definition, but the essential point remains the same. *Because the definition is sharp at the centre and edge of the field it cannot be assumed that the definition will be good in the intermediate regions.* And when considering a claim that astigmatism has been corrected in a lens the limitations of such a correction, as explained in this section, should be borne in mind.

It is worth while dwelling on astigmatism because in practice we are concerned not so much with the definition of a point, but with the definition of the edge of an image, and it is astigmatism that deals with this aspect of lens definition.

Distortion

The last of the aberrations that are not concerned with colour effects is distortion, and it is probably the easiest to describe and deal with.

What has gone before has dealt with the quality of the

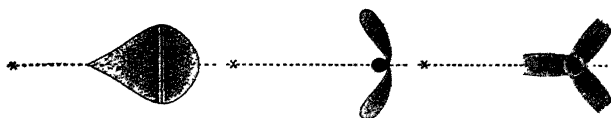
image, from the point of view of perfectly sharp rendition. In dealing with distortion attention is directed to the truth of the definition as reflected in the faithful reproduction of the shape of the object being photographed.

Since an object point in front of the lens has as its image a patch of light on the focusing screen or sensitive material, the first question to settle is: what is the shape of the image when it is not perfectly defined? How can the position of the light patch be located?

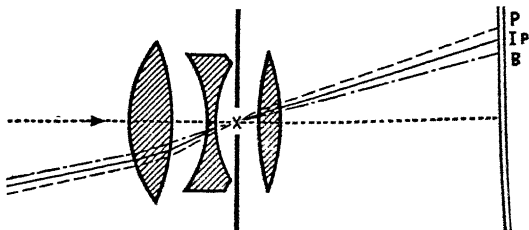
The method of fixing the image shape and locating the image of a point is to stop the lens down so that only a single ray of light can get through. This is the *principal ray*. In actual practice this is something that cannot be realised as it is not possible to define anything like the diameter of a ray of light. But if the lens is stopped down to about $f/64$ the rays that go through it are following so nearly the same path that it is not stretching things too far to think of them as being a single ray filling this small lens aperture.

Focus the lens on the plate so that the central definition is at its best. Then the point where the principal ray cuts the plate is the position of the image point. The convention is adopted that further rays, that get through when the aperture is opened out, serve only to mar the definition of the image and not to disturb its position.

The image may be either nearer to, or further from the axis of the lens, than the position it would occupy if the shape of the image were exactly that of the object. Call this last position the ideal image position. The two possibilities are shown on p. 121. In either event the deviation of the actual image position from the ideal position increases rapidly as they move away from the lens axis. From this it follows that when the actual position is further away from the lens axis and the centre of the negative than the ideal position, the lens suffers from pin-cushion distortion: a square grille of lines in front of the lens is reproduced with the shape shown on p. 121. When the actual position is nearer to the lens axis than the ideal position the lens suffers



In the presence of higher-order coma and astigmatism light patches are produced which are of a complicated shape and character. As the size of the lens aperture is decreased the size of the light patch decreases until the stage is reached when only one ray gets through the Iris, diaphragm or stop, and (neglecting diffraction) the light patch becomes a point (p. 118).



The only surviving ray when the iris diaphragm is stopped down to the limit is the *principal ray*. It locates the position of the light patch. If the principal ray cuts the sensitive material at *P* farther away from the axis than its ideal position *IP* there is *pincushion distortion*. If it cuts at *B* there is *barrel distortion* (p. 120).



The pattern on the *left* is due to pincushion distortion, that on the *right* to barrel distortion (p. 120).

LIGHT PATCHES AND DISTORTION

from barrel distortion, and a square grille of lines is reproduced with the shape shown on p. 121.

Exactly the same results hold when the lens aperture is opened out and the definition falls off slightly. A grille of straight lines is reproduced with just the same types of shape as those shown on p. 121.

Zonal distortion effects are of negligible importance in dealing with photographic lenses.

In practice most modern lenses of good quality possess only traces of distortion, and to detect it needs a careful and scientific examination. (Telephoto lenses are an exception. See p. 194.)

Chromatic Correction

The last types of fault that may afflict a lens are those connected with the unequal bending of light of different colours by the same piece of glass, as explained on p. 100.

The difference in bending for different colours varies from glass type to glass type, depending on the Abbe number as already explained. For instance on p. 123 the relative positions of red, yellow and blue images are shown as they are produced by two converging lenses of the same power, but of different glasses. The first glass is a hard crown glass with an Abbe number of 60.3, and the second an extra-dense flint glass with an Abbe number of 32.5. The coloured images are much more widely spread out in the case of the second glass, it is more "dispersive." The curves at the right of each diagram show in a more evident way how the images creep nearer to the simple lens as the colour deepens from red to blue and violet.

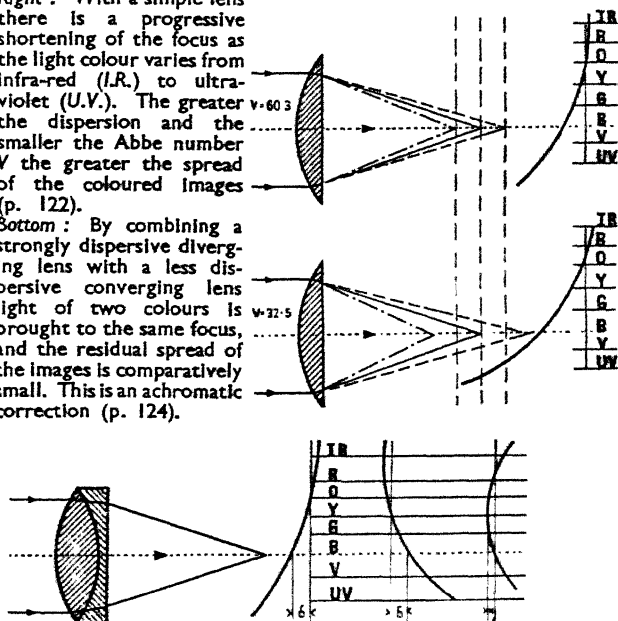
Now suppose that two lenses are combined. The first is a converging lens of crown glass. Left to itself it produces images that come nearer to it as their colour shifts towards the blue end of the spectrum. The second is a diverging lens that tends to throw the images further away as their colour tends to the blue, and is made of flint glass. The behaviour of the two lenses is represented on p. 123. The two lenses are producing opposite effects.

| WAVE-LENGTH OF LIGHT IN ANGSTROM UNITS | | | | | | | | | |
|----------------------------------------|------|------|-------|--------|------|------|----------|------|-------------|
| 4000 | 4500 | 5000 | 5500 | 6000 | 6500 | 7000 | 7500 | 8000 | |
| ← ULTRA-VIOLET | h | g | F | e | D | C | B | A' | INFRA-RED → |
| VIOLET | BLUE | BLUE | GREEN | YELLOW | RED | RED | DEEP RED | | |

Top : The wavelength of light can be described by stating in what part of the spectrum it lies. This latter contains a number of well-defined positions, specified by the so-called spectrum lines or Fraunhofer lines.

Right : With a simple lens there is a progressive shortening of the focus as the light colour varies from infra-red (I.R.) to ultra-violet (U.V.). The greater the dispersion and the smaller the Abbe number V the greater the spread of the coloured images (p. 122).

Bottom : By combining a strongly dispersive diverging lens with a less dispersive converging lens light of two colours is brought to the same focus, and the residual spread of the images is comparatively small. This is an achromatic correction (p. 124).



CHROMATIC ABERRATION

Because the glass of the diverging lens is of greater dispersive power than that of the converging lens, the power of the former can be less than that of the converging lens and yet the distance between the blue and red images can be the same in each case. Then if the two lenses are put together they form a compound converging lens. The crown glass part of this compound lens tends to make the blue images nearer to the lens than the red images. The flint glass part tends to make the blue images further away from the lens, as shown on p. 123. These two tendencies can be balanced, with the net result that the blue and red images lie in the same position, as illustrated.

This bringing images of two different colours to the same focus is spoken of as "achromatising" the lens, and a lens in which this has been done is an "achromatic lens" or "achromat." All camera lenses to-day, except on the very cheapest and simplest kinds, are achromatised.

There are two ways of looking at the achromatism of a lens, and of judging its value.

The first is in connection with photography using ordinary process, and orthochromatic plates. The maximum sensitivity of these plates lies at the blue end of the spectrum. The maximum sensitivity of the eye lies more in the apple-green and yellow region of the spectrum where the light wave-length is about $1/50,000$ inch. If the images formed by the lens for colours in these two regions do not coincide the focusing cannot be done in a straight-forward way on a focusing screen as used in either a normal or reflex camera. The eye picks out the best focus for greenish-yellow light, and the plate uses the best focus in the blue or violet regions of the spectrum. If these are not in the same place the definition on the plate is not sharp when the image is sharply focused on the focusing screen.

The regions of the spectrum, with their different colours, are described by spectrum lines that can be produced easily under laboratory conditions, and that lie in the particular region to be discussed as far as colour is concerned. For instance, the yellow region of the spectrum can be taken as

centring round the *D*-line. This is a spectrum line of bright yellow colour given out by sodium compounds in a gas flame. There are a number of important lines marking off regions in the spectrum.

For many years the practice has been with photographic lenses to bring the images of the colours centring round the *D* and *F*, or *D* and *G* spectrum lines to the same focus. This was the standard achromatic correction.

With a lens needed for purely visual work, such as a telescope or binocular objective, or a projection lens, the correction normally employed is to bring the images of colours centring round the *C* and *F* lines to the same focus. Such lenses are not really suitable for photography although they can be adapted to it by using a green filter and a panchromatic plate.

Secondary Spectrum

With panchromatic materials and films for colour photography, the other aspect of achromatism becomes of importance, and that is the size of the secondary spectrum.

It has been explained above how the achromatic correction of a lens is brought about. In the case of a more complex lens the procedure is the same in principle as that described for a compound lens, and illustrated diagrammatically on p. 123. Converging lenses are combined with weaker diverging lines made of glass of greater dispersive power. The converging lenses pull the blue images nearer to the lens than the red images, and the diverging lenses throw the blue images further away from the lens. The two tendencies can be represented by curves such as those drawn on p. 123. A suitable choice of the powers of the diverging elements results in images of two colours being brought to the same focus.

If the curves showing the tendencies of the converging and diverging lenses were the same shape, then bringing images of two colours to the same focus would automatically result in the images of all other colours coming to that same focus.

In actual fact the two curves are not the same shape, and all the images of different colours do not come to the same focus. The effect is shown on p. 123. Suppose that the images of the colours centred around the C and G lines are brought to the same focus, then images of colours between these limits come to foci nearer the lens than the common C and G focus, and the images of colours outside these limits come to a focus further away from the lens.

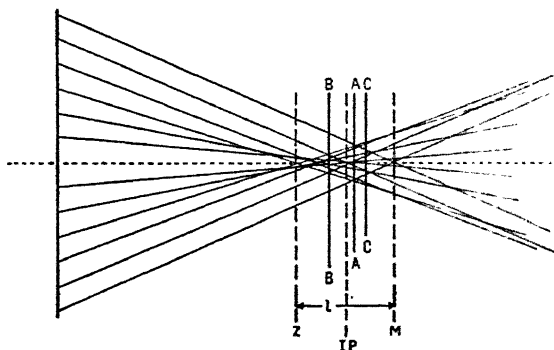
This residual spreading out of the coloured images, when two of them have been brought to the same focus, is the "secondary chromatic spectrum." It is of importance in dealing with films and plates that are sensitive throughout the whole spectrum, as with panchromatic and colour negative material. To flatten out the secondary spectrum the colours centred about the C and G lines are brought to the same focus. And for critical work special lenses have been designed. Up-to-date lenses pay more attention to this flattening of the secondary spectrum than those of an earlier date, and it is worth bearing this in mind when critical definition is needed with colour material.

When a very high degree of flattening of the secondary spectrum is required as in process lenses an "apochromatic" correction can be used. In this coloured images of three different colours are brought to a common focus.

Lenses such as process lenses in which there is an apochromatic correction are restricted to apertures of about $f/11$ and smaller. Since the war, fully apochromatic lenses have also been produced for general, and especially colour, photography. Special design is required to allow for different degrees of spherical aberration with different colours.

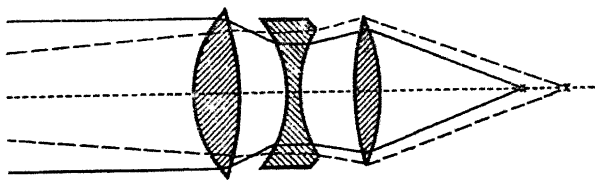
In spite of the complication of this variation of spherical aberration the results given above still hold in general. Images of different colours lie at different distances from the lens. The spread out of these images is reduced by bringing two of them to the same focus, and this leaves then only the secondary spectrum.

This is the *axial chromatic aberration*.



The rays from any actual lens do not meet in the sharp point anticipated by depth of focus calculations, but meet the lens axis from *Z* to *M* over a distance *l*. There is thus produced a light patch of varying size and density on any of the planes *AA*, *BB*, or *CC*. Ideally all the rays should meet in a point on *IP* (p. 129).

RAY OF LIGHT NEAR A FOCUS



The diverging rays from a point near a lens cut the lens surfaces at different heights to parallel rays from a distant point. As a result the aberrations produced at each surface are different and their delicate balance upset as a rule. It is for this reason that many camera lenses are unsatisfactory as enlarger lenses. The extent to which the balance is upset depends on the exact lens construction and it is practically impossible to make general rules. The effect usually does not become of importance until the distance of the object point is less than about six to eight times the focal length of the lens (p. 134).

RAY OF LIGHT FROM NEAR AND DISTANT POINTS

Lateral Chromatic Aberration

There is in addition another quite independent effect, the *lateral chromatic aberration*.

The axial chromatic aberration takes care of the positions in which the images are formed. But it may happen, assuming that the axial aberration has been corrected, that each individual ray going through the lens from a point away from the lens axis is split up into a group of coloured rays, and these produce a spectrum on the plate. This has already been described on page 101. The blue end of the spectrum may be nearest to or farthest from the lens axis depending on the position of the stop limiting the rays.

To correct the lateral chromatic aberration groups of lenses, not necessarily restricted to being convergent or divergent, are used which have opposing tendencies. One set tends to produce a spectrum with its blue end nearer the lens axis. The other tends to produce a spectrum with its red end nearer the axis. The two sets are balanced so that the two tendencies neutralise one another and the spectrum is folded back on itself. For instance, the rays of coloured light centred about the *C* and *F* lines may be brought to the same focus on the plate. This does not mean that all other colours will come to the same point. Again in this case there is a lateral chromatic secondary spectrum. It is of quite negligible importance except in very rare instances in scientific work.

The main things to look for in testing a lens as far as chromatic aberrations are concerned are the achromatism, the axial secondary spectrum especially where colour film is used, and the lateral aberration, which again is of importance with colour film. Lateral aberration that does not show up in black and white to any great extent produces images with badly coloured edges with colour film or images of different size on the different plates of a set of separation negatives taken through red, green, and blue filters respectively. The actual testing of lenses for chromatic aberrations is described on pages 236 and 239.

Aberrations and Depth of Field

Now that the aberrations have all been described the time is ripe to say a few words more about depth of field.

The method of calculating depth of field was described on pages 66 and 69 for the two usual cases. In the first the calculation is based on the convention that the print is to be enlarged to get the correct perspective at the closest viewing distance of 10 inches. In the second the calculation is based on the assumption that the grain size of the film limits the size of the light patch to a minimum of either .002" or .001". But in both calculations it is assumed that the lens is perfect, that rays of light going through the lens all come together in a point. This cannot be realised in practice.

The lens suffers from aberrations that have to be balanced one against the other, and that cannot be eliminated. The rays do not converge to exact points but cut any plane in a light patch of finite size, and it cannot be taken for granted that this will not influence the results of the calculation of the depth of field.

Consider for instance the simplest case of a lens with an appreciable amount of zonal and marginal spherical aberration in it. The spherical aberration is under-corrected for rays through intermediate zones of the lens aperture, and slightly over-corrected for rays through the margin of the lens. This is the normal type of correction encountered in practice. The exact arrangement of the rays near their ideal focusing point is shown on p. 127.

What corresponds to a focus in a lens with this type of aberration is the position where the bundle of rays has its smallest diameter, as shown at AA on p. 127. The image at this point is a small hard disc of light. When the focusing screen is moved to the position BB on p. 127 the light patch obtained consists of a small bright core surrounded by a diffuse halo. When the focusing screen is taken still further away the light patch increases in size and becomes a fairly even disc of light. With the focusing screen at the position CC the light patch is an even disc with slightly woolly edges.

This is not the type of performance contemplated in calculating the depth of field scales on page 68. What is envisaged there is an absolutely sharp focus at the image point and a perfectly even disc of light when the focusing screen is either inside or outside this image position.

The net result obtained with a lens having the correction described above is that images of objects in the centre of the field, nearer to the camera than the object on which the camera is focused, are sharper than objects the same distance farther away from the camera. There is an unequal balance between foreground and background, with the foreground better defined. This is the reverse of what is usually desired in practice, where the definition of the background is preferably to be maintained. A lens has been designed (Taylor, Taylor & Hobson) to provide this latter type of correction by making the zonal spherical aberration over-corrected and the marginal rays under-corrected. To do this, however, means using non-spherical surfaces with greatly increased manufacturing difficulties.

To get an estimate of the importance of the spherical aberration the best thing is to deal with some figures, and numerical results that can be expected for typical lenses.

It follows from the results quoted in the section on depth of field that the distance between the images of the nearest and farthest points that are in sufficiently sharp focus is given approximately by,

$$\text{Separation} = 2 \times (\text{focal length}) \times (\text{stop No.}) \div 1000 \text{ in.}$$

In a 2 inch $f2$ lens as used for miniature cameras this gives a separation between the two images of $2 \times 2 \times 2 \div 1000$, i.e., .008 inches. With a good quality lens of this type the zonal aberration, or the distance between the points where the largest and shortest foci lie for different rays through the lens, as shown on p. 127, may be expected to have an average value of about .004 - .006 inch. That is to say, the region over which the rays are coming to the waist of the bundle, as shown on p. 127, has a size that is about half the length allowed for by the depth of field calculation

of the image separation. This must have a definite effect on the depth of field of the lens. And quite apart from the difference in size of the light patch when there is spherical aberration present, to that envisaged by the methods referred to on pages 66 and 69, there is the complicating factor that the distribution of light in the image patch is not the even filling of a disc envisaged there.

When the $f2$ lens considered is stopped down to $f2.8$ or $f3$, that is when the aperture is reduced to one stop below its maximum, the zonal aberration is usually cut down very considerably and at the same time the distance between the images of permissible quality goes up by nearly 50 per cent. The spread of the zonal spherical aberration effect, relative to the image separation permitted by the depth of field as calculated on pages 66 and 69, is much smaller. The depth of field calculated is giving a more exact picture of the actual limits of passable definition. By the time the lens is stopped down to $f4$ the orthodox depth of field calculation is giving a very good approximation to the depth of field actually obtainable with the lens.

With a lens, say a 4 inch $f2$, all that has been said above holds in principle. Because of the greater focal length, 4 inches compared with 2 inches, the separation between the images of the nearest and farthest objects in reasonable focus is doubled, and is now .016 inches. At the same time the spherical aberration spread-out is scaled up two-fold. The ratio of the two is unchanged and as a consequence the conclusions already given are unchanged.

With a lens of lower aperture a simpler construction is usually adopted than that needed to give good results at an aperture of $f2$, and as a rule something, although not very much, is lost in the way of minimising the zonal spherical aberration. The results are along the lines of those already given for $f2$ lenses.

As far as depth of field is concerned near the centre of the field a rough rule is this ; at apertures up to $f8$ the orthodox calculation of the depth of field gives results that are a very good approximation to the truth ; between $f8$ and $f4$ the

calculation holds very well for the lens stopped down to the largest but one aperture ; and for apertures from $f\ 4$ to $f\ 1.5$ the calculation gives good results for the lens stopped down by two stops.

For apertures outside the range where the old-style calculation holds good, and even perhaps for the largest aperture in this range, the only way to settle the depth of field is by direct experiment (pp. 260-264).

Depth of Field in Practice

Even that does not finish everything. What has been said above is for depth of field in the centre of the field. This, of course, is important. *But equally important is the depth of field away from the centre of the negative, the depth of field in the foreground and background of the principal subject.* There are two comments to make on the value of the orthodox calculation in this respect.

In the first place the depth of field calculated as on pages 66 and 69 holds good if the lens brings all rays to a point focus, and if away from the centre of the negative the lens still passes the same amount of light. In actual fact it does not do so. As explained more fully on page 254 the lens aperture is effectively less when the image point is away from the centre of the field, except in some special cases. This tends to increase the depth of field.

In the second place there are two types of definition away from the centre of the field, as explained in the section above dealing with astigmatism. Either radial or transverse lines may be better in focus when the plate is moved from its ideal position. In a 2 inch $f\ 2$ lens the shift of one of the images planes from its ideal position may amount to .003 inches to .004 inches, and the separation between the two may be .008 inches. This is just the image separation demanded by the depth of focus calculation, and it naturally affects the validity of the depth of field calculation. By the time that the lens has been stopped down to $f\ 8$ the depth of focus separation between the images has gone up four-fold, but

the separation of the astigmatic image surfaces is unchanged and has much less influence on the validity of the calculation.

As far as average definition is concerned, the values obtained from the central field calculation, taken in conjunction with the remarks relative to this given above, give a moderately good approximation to the truth. The definition is of too complicated a nature, with the entry of astigmatism and vignetting (although the latter is small over most of the field) to say anything more precise.

Depth of field tables have been of great use to photographers for many years, but their limitations must be realised. These are mainly connected with large aperture lenses. The early ideas and most of the present ideas about depth of field date from the days when an $f/7.7$ lens was considered to be reasonably fast—apart from Petzval portrait lenses covering a small field. Things have changed since then and a modern lens can hardly be considered fast with an aperture below $f/1.4$ to $f/2.5$. The influence that this change of lens aperture has had on the validity of depth of field calculations must be taken into account, and the reliability of depth of field tables for large aperture lenses must be judged by what has been said above in this section.

Camera Lenses in Enlargers

It is a well-known fact that a lens that gives excellent results in a camera may give results in an enlarger that are definitely not first class.

It is not exactly fair, however, to expect a camera lens to give results of the highest quality when it is used in an enlarger. It is working under quite different conditions from those for which it has been designed.

The normal photographic lens is designed to photograph objects at a considerable distance from the lens. It is on this assumption that rays are traced through the lens, that the heights are noted at which these rays hit the various refracting surfaces, and that the deviations which the rays undergo at each of these surfaces are measured. And the aberrations depend on these.

At the various lens surfaces aberrations of all the types described earlier in this chapter are introduced, usually in very considerable amounts, much greater than the amount of any of them that is left in the lens as a whole. These aberrations that are introduced surface by surface have to be balanced against one another very carefully indeed to get the final correction of the lens. And this balancing is usually done under the prescribed conditions, namely that the object in front of the lens is at a large or infinite distance, and that this fixes the incidence heights and bendings at the various surfaces. The final correction is sensitive to changes in these things.

On p. 127 are shown the paths traced by two rays through a lens, one from a distant point on the lens axis, the other from a near point. The deviations between their paths through the lens are shown on an exaggerated scale. In actual practice they are much smaller, but still quite large enough to be significant and to affect appreciably the lens performance. The delicate balance of aberrations is upset and the quality of the lens performance is changed to a greater or less extent.

Among other things the spherical aberration and axial chromatic aberration correction may be upset. Taking these two only it is possible to design a weak supplementary lens to correct them if it happens that the camera lens is not giving the highest standard of definition when used at full aperture. A lens of this type was supplied for instance by Zeiss for use with the 2 inch $f/2$ Sonnar lenses such as are used on Contax cameras. It is a more difficult job to take care of changes in any of the other aberrations, and if they are very heavy the lens is not suitable for enlarging purposes.

With a normal type of photographic lens the definition is maintained fairly well until the distance of the object from the front of the lens is seven or eight times the focal length of the lens. At closer distances the chances are, except in some individual cases, that the definition falls off. This means that when using the lens to make enlargements satisfactory results should be obtained with a good camera lens for

enlargements with a magnification of six or seven diameters upwards. For lower degrees of enlargement the lens may not give really good definition without stopping down.

Enlarging and Process Lenses

For those occasions when the very highest performance is needed in enlarging work special lenses have been designed to work under these conditions. They are designed so that when the distance from the negative to the enlarging board is about 4 times the focal length of the lens, when the lens is giving either a reduced size image on the enlarging board, or a slightly enlarged image, the lens correction is established.

The main aberrations to which special attention has to be paid in an enlarging lens are the chromatic aberrations, both axial and lateral, although the correction of the other aberrations has also to be maintained well up to the standard of the best photographic lenses.

The focusing of an enlarger lens is always done visually, and the region of the spectrum to which the paper is sensitive is not that to which the eye is most sensitive. As already pointed out this requires that to get good results the lens must be achromatised for these two regions. The chromatic correction is of such importance in process lenses that in some of them an apochromatic correction is established.

When the enlarger lens is to be used in colour work, especially in the making of separation negatives, the lateral chromatic aberration must be very highly corrected, to a degree higher than that which often suffices in photographic lenses of the same aperture and covering the same field. When a lens is used in a camera to photograph distant objects the spread of the spectrum may be quite small and less than that of the size of the emulsion grain. When the same lens is used for enlarging the spread of the lateral aberration spectrum is also enlarged and may very easily reach inadmissible dimensions. Hence the importance of dealing thoroughly with lateral chromatic aberration—the

more since it cannot be remedied by stopping down the lens.

The best way to deal with the way in which the lateral chromatic aberration is enlarged is to give some figures. It may very easily happen that a camera lens of 4 inch focus say, when used between comparatively near object and image planes has a spectrum covering .0025 inches. This means that if the lens is used in an enlarger to give a ten-fold enlargement the spread of the spectrum is one-fortieth of an inch. Such a spreading of the image, which is quite unaffected by stopping down the lens, would be quite fatal in exact colour work of any sort.

And finally there is one recent development that may emphasise also the importance of the chromatic correction of a lens under enlarging conditions, and that is the introduction of variable contrast papers.

The Problem of Variable Contrast Papers

With ordinary papers the situation as regards chromatic aberrations and their corrections is eased, as far as black and white work is concerned, by the limited region of the spectrum to which the paper is sensitive, in the deep blue mainly. The variable contrast paper depends for its operation on the fact that it is sensitive to two regions of the spectrum. It comprises in effect two emulsions, one of hard contrast sensitive to one region of the spectrum, and another of soft contrast sensitive to quite a different part of the spectrum. The lens is used with filters which transmit light that is a mixture of both regions of the spectrum in varying proportions, according to the individual filter used. As a result the enlargement is given a mixture of hard and soft contrast in proportion to the amount of light from each region of the spectrum that the filter transmits to it.

The importance of the correction of the chromatic aberration as far as using this type of paper is concerned is obvious. Lack of correction that might not be seen with normal black and white papers may show up as a relative displacement of the regions of hard and soft contrast.

While it may happen that a camera lens will give good results in an enlarger it cannot be taken for granted that it will do so. And the converse holds, it cannot be taken for granted that an enlarger lens will give passable results in a camera. Each is best relied upon for the specific job for which it was designed.

Definition and Stopping Down

One topic to which a few words should be devoted is the effect on the definition of stopping the lens down.

The general rule is that as a lens is stopped down the definition it gives is improved. The size of the light patch given by any of the aberrations is decreased as the lens aperture is reduced, with two exceptions. Lateral chromatic aberration and distortion are completely unaffected by stopping down the lens. Spherical aberration and coma are most rapidly affected by stopping down the lens, astigmatism is changed much more slowly.

The net result is that with lenses of apertures below about $f/3$ it can be taken as a safe rule that there will be a progressive improvement in definition as the lens is stopped down. With lenses of higher aperture, up to $f/1.4$ and even larger apertures, it is sometimes found that the definition improves as the lens is stopped down, say from $f/1.5$ to $f/3$, remains at this as the optimum definition that it can afford, until the lens is stopped down to about $f/6$, and then falls off again.

This type of behaviour is often passed off too glibly, as being due to diffraction, and it is worth looking into the matter rather more closely at this stage.

Diffraction

There are two opposing tendencies at work that map out the behaviour of light. The first is the fact that light tends to travel in straight lines along the so-called rays of light, and as a result of this to form sharp and well defined shadows.

The second tendency is for the light to spread round the edges of any obstacle casting a shadow, to curl round and give a shading at the edge of the shadow so that this latter is no longer clear cut. For instance under carefully arranged conditions it is found that at the centre of the shadow of a disc, such as a sixpence, there is a bright spot of light produced by the light that spreads round the edge of the disc. This was first deduced on theoretical grounds and seemed to mean the end of that particular theory, but it was later checked by experimental work.

The spreading of light at the edges of an obstacle is known as the "diffraction" of light, or simply as "diffraction."

In the vast majority of photographic phenomena the diffraction of light is not of major importance. The size of the effects it produces is so small in general compared with the effects produced, for instance, by the aberrations of a lens used at full aperture, that it can be left aside. But there is one important feature about diffraction that has to be taken into account, and that is the fact that as the lens is stopped down the size of the diffraction effects increases.

Neglecting all lens aberrations and assuming that it is perfect, then because of the diffraction of light the lens produces, not a point image, but a disc of light in the centre of the negative, the "Airy disc," the diameter of this is given by the formula :

Diameter = .000045 \times (Stop number of lens) inches. For instance with any perfect $f/4$ lens the diameter of the Airy disc when the lens is working at full aperture is .000045 \times 4 = .00018 inch.

Stopping down the lens and so increasing the stop number of the lens means that the diameter of the Airy disc is increased, and it is this fact that has sometimes been seized upon to account entirely for the falling off in performance with decreasing aperture. But against accepting this explanation completely there are some further facts to consider.

In the first place the effect is not invariably found even with short focus on large aperture lenses. For example, the earliest 2 inch $f/1.5$ Zeiss Sonnar cannot be stopped down

below $f/11$, but the 2 Inch $f/2$ *Sonnar* can be stopped down to any required aperture without upsetting definition. In the same way the *Kodak 45 mm. f/2 Ektar*, the *Dallmeyer f/2 Super Six*, and the *T.T.H. Cooke Series 0 f/2* can be stopped down to $f/16$ and lower apertures. If the effect were due to diffraction alone the limitations that it puts on lens performance should be universal, and not varying from lens to lens.

In the second place it is often noticed that the definition on an overexposed plate is of lower quality than that on a correctly or underexposed plate especially when an emulsion of moderate or hard contrast is used. Part of this is due of course to such things as scatter within the emulsion ⁽¹⁾, but it cannot be entirely attributed to this in all cases. The light patch on the sensitive material may have quite a complicated structure owing to the balancing of aberrations, as already explained. Added to this is the light distribution owing to rays which undergo two reflections at air-glass surfaces in the lens.

With the lens at full aperture, and with correct or insufficient exposure the fainter parts of the light patch do not register, no matter what their origin. When, however, the lens is stopped down, the balance of light distribution may change. For instance, there may be a ghost image formed by reflection at two of the surfaces, which is not too far out of focus, and which has, say, rather heavy spherical aberration. With the lens at full aperture, the contribution of the light in this ghost image may be swamped by light from the marginal parts of the lens aperture. But on stopping down the lens the balance may be changed, and the contribution of this ghost may be appreciable. This seems to be the case, for instance, in the earlier 2 Inch $f/1.5$ *Sonnar* lenses, where the contribution of the ghost image in the centre of the field restricts the extent to which the lens can be stopped down,

(1) Scatter within the emulsion, etc., is dealt with in another volume of this Manual. *Developing : The Negative Technique* by C. I. Jacobson (Focal Press), and reference should be made to this for that particular aspect of definition.

and still give satisfactory definition. The intensity of the ghost is considerably reduced by coating the air-glass surfaces, and a *Sonnar* lens treated in this way can be stopped down further than an untreated lens.

The variation of one aberration must be regarded when considering stopping down a lens, namely of axial chromatic aberration. In most lenses the axial chromatic aberration of the innermost zones of the aperture is left under-corrected to counter-balance the variation with colour of spherical aberration. The correctly balanced outer zones at full aperture send so much light to the sensitive material, that it over-shadows the under-correction of the inner zones. Removing this outer-zone light by stopping down the lens, leaves the chromatic under-correction which may become apparent with critical examination of the image normally associated with stopping down.

As a rule it is only with extreme aperture lenses that trouble is encountered on stopping down. It may be met with in lenses of aperture $f/3$ or $f/4$, but only in traces, and should not be troublesome as long as the lens is not stopped down so far that the diameter of the Airy disc due to diffraction becomes appreciable.

Diffraction is of importance where enlarging is concerned, because the demands on lens performance in making critically sharp enlargements are such that attempts are made to meet these demands by stopping down the lens to the point where diffraction rather than aberrations limits its performance. The light transmitted by an enlarging lens under these conditions spreads out into a diffraction disc on the enlarging easel. If the degree of enlargement is M diameters, and the lens is working at f/N , then the diameter of the light patch is $N \times (M + 1) \times 0.000045$ inches. Thus for a lens working at $f/22$ giving a ten-fold enlargement, the diameter of the diffraction patch is approximately 0.01 inch, which gives an appreciable degradation in the quality of the enlargement if this is critically examined. Note that the diameter of the diffraction patch depends only on the f number, and not on the focal length of the lens.

BASIC LENS TYPES

Primitive Lenses

The simplest kind of lens is a burning-glass, a piece of glass polished on both sides to convex spherical surfaces. This is useless for all but the crudest type of photography. As a lens it suffers heavily from every type of aberration, and in particular from spherical aberration and axial chromatic aberration, both of them strongly under-corrected. In other words the rays through the edge of the lens come to a decidedly shorter focus than do the rays through the innermost zones, and the blue image is much nearer the lens than the images formed by yellow or red light.

It is possible to alleviate the spherical aberration somewhat by making the lens nearly convex and plano, that is with one surface of convex spherical shape and the other practically plane or flat. This does nothing to help the axial chromatic aberration.

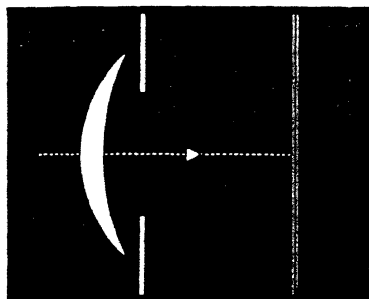
Such a lens can be used, in the form of a spectacle lens for instance, with a crude form of camera provided that it is stopped down to about $f/16$, that critical definition is not required (the standard of definition given then is about that of a snapshot with a cheap camera), and that no visual focusing is attempted. The definition in the field away from the centre of the negative is poor compared even with the central definition given by such a lens.

The best compromise with a single glass lens, such as used in cheap and simple cameras is to use a meniscus lens either with the stop behind the lens or in front of the lens as shown on p. 143. When the aperture stop is at a suitable distance from the lens, astigmatism and coma can be reasonably well corrected. Spherical and chromatic aberrations, distortion and field curvature remain uncorrected and the lens can only be used at very small aperture stops. Such lenses cannot be considered in any way where serious work is concerned but they can give satisfactory results on cheap box cameras.

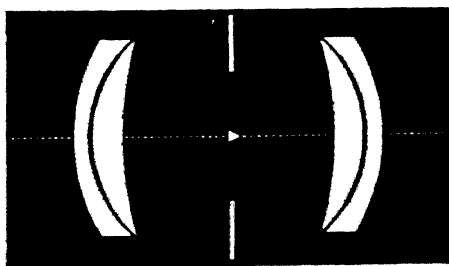
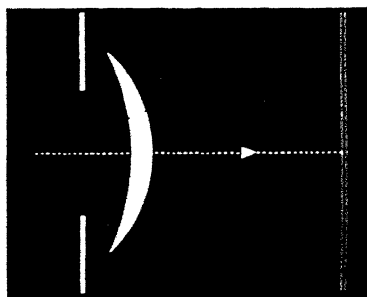
The next type of lens in the order of simple and primitive construction is a compound lens corrected for achromatism and spherical aberration. It is possible by a judicious choice of glasses to obtain quite a good correction for coma with this type of lens, but in spite of this such a construction has not been used appreciably for photographic lenses. The main troubles are still astigmatism and distortion.

What was used extensively during last century was a lens consisting of two identical doublets with a stop between them as shown on p. 143. This is the "R-R" or *Rapid-Rectilinear* form of lens, invented by *Dallmeyer* and *Steinheil* in England and Germany respectively. With such a construction coma, distortion and lateral chromatic aberration are very thoroughly corrected, and by a suitable choice of glasses for the lenses astigmatism, as defined in the previous chapter, is removed. Axial chromatic aberration is also corrected. What remains is to correct the lens for spherical aberration and pure curvature of field. This cannot be done entirely. The spherical aberration correction in particular limits the lens to a maximum aperture of about $f8$. The field curvature can be artificially removed by introducing astigmatism as explained in the previous chapter, but to do this means introducing a considerable amount of astigmatism, much larger than that found in any modern anastigmat. While a coma-free field of about 40° total angle can be obtained the astigmatism or curvature of field, whichever is left in the lens, softens the definition considerably in the outer regions of the field.

The lenses described above, together with Petzval lenses described below, did sterling work in the early days of photography. But to-day neither rapid-rectilinear lenses nor single glass lenses can be considered where serious work is intended. The standard of definition or speed demanded of, and supplied by, a modern anastigmat far surpasses that which sufficed when these were standard lenses. They now belong to history. Second-hand R-R lenses are, however, quite useful when a cheap lens is needed to cover only a small field with an aperture of $f8$ to $f11$.



Left : The simplest and crudest types of camera lens are meniscus lenses with a stop in front or behind (p. 141).



Above : The rapid-rectilinear lens consisting of two doublet members symmetrical about a central stop can now be regarded as obsolete (p. 142).

PRIMITIVE LENSES

Petzval Lenses

The original Petzval lens was designed by the Hungarian *Joseph Petzval* in 1840, and was intended as a portrait lens with the large aperture, for those days, of anything up to $f3$. Its construction is shown on p. 145, Pl. The basic design remains the same at the present time although there have been, of course, numerous detailed changes made to obtain a standard of definition more in line with modern requirements.

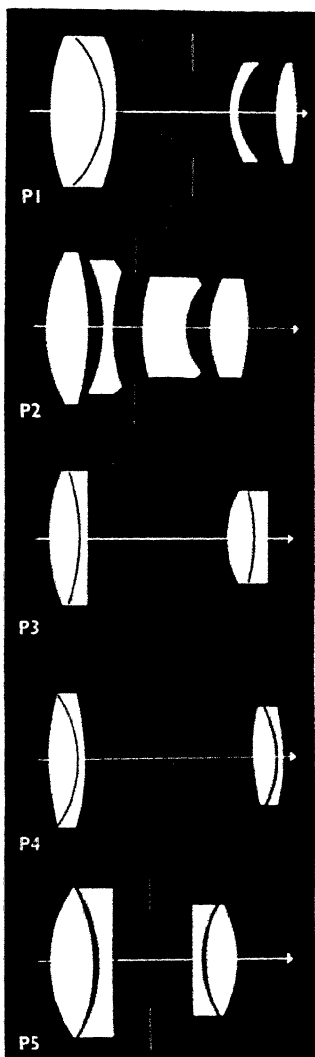
Essentially it consists of two sets of lenses, each set separately achromatised, with a comparatively large separation between them. In some cases a stop is placed between the two sets, but in the majority of cases this is dispensed with.

The Petzval lens is still in use to-day as a photographic lens. At one time variations of this construction were used as portrait lenses having the characteristic of sharp definition in the centre of the field falling away towards the edges. More recently this form has been largely superseded by modern constructions covering wider fields of view and yielding the required amount of softness of definition evenly over the field.

This form of lens has been modified to make good use of modern glasses and several lenses are now in use on 8 and 16 mm. movie cameras where the rather long overall length of this type of lens is not a serious disadvantage. The relative aperture of this construction can now be increased to about $f1.5$.

Projection Lenses : The lenses just mentioned are corrected, of course, for photographic work as far as chromatic aberration is concerned. *But the vast majority of Petzval type lenses now on the market are intended as projection lenses, and are corrected for visual use only, as far as chromatic aberration is concerned. They are not suitable for this reason as photographic lenses. It is important to notice this, because if it is not taken into account the Petzval type of projection lens, with its wide aperture, and in many cases comparatively low price, may seem a tempting*

The diagram P2 of a *Dallmeyer* 8 mm. cine lens indicates how the original Petzval lens P1 can be modified to give improved performance. P3 and P4 are modifications of an early form of microscope objective which is classified under this heading. They are applied largely to cine lenses. P5, as exemplified by certain *Aldis*, *T.T. & H.*, and *Wollensak* projection lenses, indicates a hybrid between P1 and P4.



PETZVAL TYPE LENSES

bargain. It is possible to use a projection lens as a photographic lens to cover only a small field provided that a filter is used that completely cuts off the blue end of the spectrum and a good part of the red. This means, however, that the total light passing power of the lens is drastically restricted even when a panchromatic plate is used, and so to all intents and purposes the effective aperture is cut down.

Petzval type lenses are made to-day for projection purposes in apertures up to about $f\ 1.6$. The projection services to which the lenses are put are mainly: (1) Slide projection as in epidiascopes and projectors of various types. (2) Miniature slide projection of coloured and black and white transparencies of standard miniature size, i.e., 24×36 mm. (3) Projection of 16 mm. and 8 mm. film. (4) Projection of standard 35 mm. professional film. There are other specialised uses, as in reading micro film, but these can safely be left out of this book. The main uses are those mentioned.

Covering Power: The methods of working out the equivalent focal length of the lens, needed to give a specified size of projection on the screen, are described on pages 57-58. They give no information at all as to whether the lens will provide sufficiently good covering power over the slide area needed, nor are they intended to do so.

With Petzval type projection lenses the general rule is that the larger the aperture the smaller the field that is covered (this is in fact a general rule about the performance of any type of lens construction).

Lantern Slides: The standard size of the frame projected in the lantern slide is about 3 inches \times 3 inches, with a diagonal of close on $4\frac{1}{4}$ inches. The minimum focal length of Petzval lens that can handle this diagonal comfortably is in the neighbourhood of 8 inches with an aperture of about $f3.5$. Diagram P5 on p. 145 shows a lens of this type which differs from the conventional form in having no pairs of glasses cemented together. A certain amount of light is lost at the extra glass-to-air surfaces but against this is set the fact that there is no chance of any cementing balsam

ageing under the effects of the heat from the lamp that is concentrated upon it. Lenses of more than 8 inches focal length, and the same or smaller aperture, will naturally cover the area of the slide rather more easily than the 8-inch lens as they are working with a smaller angular field.

In connection with this it may be remarked that in many cases, with a lens of the type just described, the relative aperture of the lens is not engraved upon the mount. This is a practice that has survived rather too long and should be discouraged. In any case with a Petzval type lens it is as a rule a simple matter to determine the numerical aperture. There is usually no complication of internal stops or irises cutting down the effective aperture. All that has to be done is to measure the clear aperture of the front glass and divide this into the focal length. For instance if the lens has a focal length of 8 inches, and the clear aperture of the front glass is 2.16 inches, then the f number of the lens is $8 \div 2.16 = 3.7$ near enough, i.e., the aperture is $f3.7$. The importance of the f number as far as brightness of projection is concerned is dealt with on page 329.

One related topic when dealing with this class of lens, namely the slide projection lens that finds its way into instruments such as epidiascopes is the type of lens available for episcopic projection. (Diascopic projection is that in which a transparency such as a lantern slide is used and the light from a lamp and condenser system goes through it to a projection lens. Episcopic projection is that in which an opaque object is very brightly lit and the light scattered from its surface is picked up by a lens and projected into an image on the screen.) The normal size of lens used in an epidiascope for episcopic projection, and one which covers a reasonable field, is between 14 inches and 20 inches focus with an aperture of about $f4$. In this size of lens it is usually much cheaper to make it of anastigmat construction in the form of a *Cooke Triplet*. A lens of 14 inches to 20 inches focal length of Petzval construction is usually of lower aperture than $f4$, and is not so fitted for use in an epidiascope as the faster anastigmat type.

Miniature Slides: Petzval type lenses find their uses also in miniature projectors for 36×24 mm. size slides. In this work the aperture extends up to about $f\ 3.2$. With such an aperture the smallest focal length of lens that can give good definition over the whole of the frame of the slide is between $3\frac{1}{2}$ and 4 inches focus. Larger focal lengths with the same or smaller apertures, as mentioned above, will cover the required area and provide satisfactory definition, as they are covering a smaller angular field as the focal length increases.

When a shorter focal length of lens than about 4 inches is needed for miniature slide projection, because of the requirements of throw from projector to screen and size of projection, an anastigmat construction of lens should be used. Details of various forms of anastigmats are given in the next two sections. Modifications of some of them are used as projection lenses when the covering power needed is greater than the Petzval construction can afford.

Many of the projection anastigmats are straightforward *Cooke Triplets* achromatised for visual use, especially when the aperture is not larger than $f\ 3$ and the focal length not less than about $2\frac{1}{2}$ to 3 inches. For larger apertures more complicated constructions are needed as in the *Leitz 8.5 cm. $f\ 2.5$ Hektor* for use in the *Leitz* miniature projector.

In many cases the miniature projectors used are adapted to take miniature camera lenses of 2 inches focus and upwards, but these latter belong to the later section of this chapter as they are primarily photographic lenses, and only incidentally projection lenses. And in passing it may be noted that the nature of the chromatic correction adopted in the respective cases of photographic and projection lenses means that, whereas a photographic lens can be used satisfactorily for projection purposes, a projection lens cannot be used equally well for photographic purposes. The visual chromatic correction is usually adopted for projection lenses.

And a word of warning may not be out of place. Caution should be exercised in using a treasured miniature lens in a cheap or badly designed miniature projector. In many lenses there are pairs of glasses cemented together with a transparent cement of Canada balsam. Any maladjustment of the condenser system that permits of light from the projection lamp, from which heat rays have only been imperfectly filtered, coming to a focus near the cemented surfaces may cause this balsam to harden in time, to become discoloured, and to spoil the definition of the lens for miniature taking work.

16 mm. Film: The Petzval type of lens finds a ready application in the projection of 16 mm. and 9.5 mm. movie-film. Lenses for this type of work range in focal length from $\frac{5}{8}$ inch to about 4 inches, and have apertures up to f 1.6. The shorter focal lengths are intended for the 9.5 and 8 mm. films, and should not be attempted on the 16 mm. film except in slightly slower apertures, up to about f 2.1. The faster lenses are of special value where colour films are concerned as these latter are not usually so transparent as black and white films.

35 mm. Film: Petzval type lenses are used exclusively in cinema projection work where front projection is concerned. They are available in focal lengths from 4 inches upwards, with steps between each focal length of $\frac{1}{4}$ inch. The maximum apertures are about f 1.9 for the shorter foci, and f 2.7 for the longer foci. A characteristic of the fastest types of this kind of lens is the step in the barrel and the short clearance between the back lens and the film gate. See P3 and P4 on p. 145.

Where back projection is required in cinema work, with the projector placed behind the screen, short focus lenses have to be used. These are of anastigmat construction usually of a complicated type, for example of the *Speed-Panchro* or *Pentac* constructions, as described in the next sections, with the possible modification in the case of the *Speed-Panchro* construction that the curves on the glasses usually cemented together may be changed so that the

lenses are no longer cemented but touch one another at their edges. This means that there is no danger of any cement ageing under the influence of the heat of the arc. Lenses for this type of work are available in focal lengths from 1 inch to $2\frac{1}{4}$ inches, and with apertures up to $f1.8$.

A recent projection lens by Aldis is referred to in a later section. This is of the telephoto construction and has the advantage that a long focal length can be used with a small extension of the lens mounting. It also permits the use of a universal condenser lens system which is suitable for more than one focal length of projection lens.

Radiography. One further use that the Petzval type of lens has been put to is in connection with very fast lenses such as are needed in photographing X-ray fluorescent screens, in producing moving pictures of processes inside the human body, and in photographing traces on the screens of cathode-ray tubes. These are essentially photographic lenses not projection lenses. The extremely wide apertures necessary for this work have been achieved by the addition of extra lens elements to the basic Petzval construction and apertures of about $f0.8$ have been produced by Taylor, Taylor & Hobson, Zeiss and others. These forms are designed specially to suit particular requirements of magnification, field and colour correction and are therefore not usually listed in manufacturers' catalogues.

To sum up the general characteristics of the Petzval and modified Petzval construction this can be said: the construction readily lends itself to the production of lenses of large aperture, with a moderate degree of freedom from all comatic effects, but the field is limited by the heavy curvature of field or astigmatism put in to obtain an artificial flattening of the field. The larger the aperture the smaller the field covered. The larger aperture 4-inch focus cinema projection lenses just manage to cover the area of the 35 mm. film frame. Most Petzval lenses now available are intended for projection work and are not suitable for photography because of the colour correction. Photographic Petzvalls available are intended for portrait work, where a softening of definition towards the

corners of the negative gives a more diffuse background, not considered a serious defect for this type of photography. Short focus lenses are also available for 16 and 8 mm. movie cameras.

XXII.—PETZVAL LENSES AND ALLIED TYPES

| Maker | Name of Lens | Focus | Aperture | Field Covered | Diagram (p. 145) |
|---------------|----------------|--------------------------------------|----------|--------------------------------|---------------------|
| Agfa ... | Ocellar II | 20-50 mm. | f1.6 | 8 & 16 mm. <i>ciné</i> | P4 |
| Aldis ... | Projection | 4-8 in. | f3.2 | — | P5 |
| Dallmeyer ... | Cine lens | 13 mm. | f1.9 | 8 mm. <i>ciné</i> | P2 |
| | Cine lens | 1-3 in. | f1.9 | 8 & 16 mm. <i>ciné</i> | P1 |
| | Macdite | 1-4 in. | f1.5 | 8 & 16 mm. <i>ciné</i> | P4 |
| Ross ... | Rosskote | 3 $\frac{1}{4}$ -7 $\frac{1}{2}$ in. | f2.2-3 | 35 mm. <i>ciné</i> | P4 |
| | Rosslite | 3 $\frac{1}{4}$ -7 in. | f1.9 | 35 mm. <i>ciné</i> | P4 |
| T.T. & H. | Cine Proj. | 1-4 in. | f1.6-2.8 | 8 & 16 mm. <i>ciné</i> | P3 |
| | Serial | 1 $\frac{1}{2}$ in. | f1.9 | 8 mm. <i>ciné</i> | P4 |
| | Telecal | 2 in. | f2. | 16 mm. <i>ciné</i> | P1 |
| Tewe ... | Telegon | 125-200 mm. | f2.5-3.2 | 8, 16, & 35 mm. <i>ciné</i> | P1 |
| | Telegon | 300-600 mm. | f3.5-5 | 24 x 36 mm. | P1 |
| Wollensak ... | Cine Raptar | 13 mm. | f1.9 | 8 mm. <i>ciné</i> | P5 |
| | Cine Raptar | 38 mm. | f1.5 | 8 mm. <i>ciné</i> | P3 |
| Wray ... | Cine Unilite | 4-6 in. | f1.9 | 35 mm. <i>ciné</i> | P4 |
| Zeiss ... | Kiproner proj. | 90-250 mm. | f1.9 | 35 mm. <i>ciné</i> | P3 |

Symmetrical Lenses

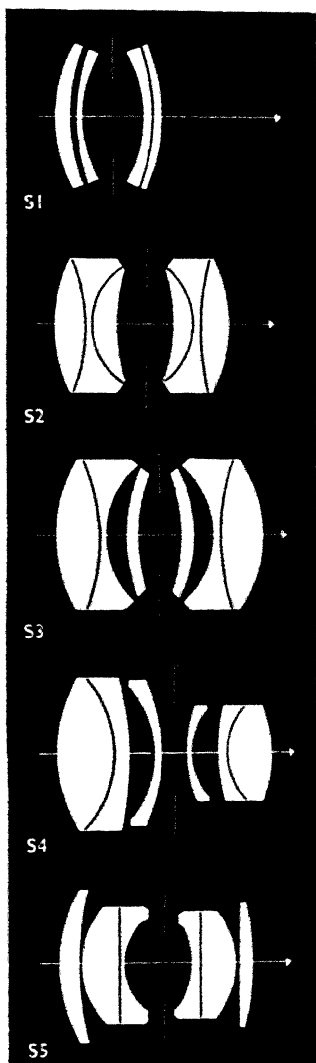
The vast majority of photographic lenses to-day are logical developments of two main types, the symmetrical lens, and the *Cooke Triplet* of *H. D. Taylor*. There are, of course, cases where it is difficult to say from which basic

type a particular lens has been derived, and in what follows a certain arbitrary element of choice must enter where such lenses are concerned. And although some lenses may be said to be derived from these basic lenses through a gradual development of the latter it must not be taken for granted that the actual development did not take place in this way. The development of better lenses is not a process that goes on in a rigorously logical way. Various advances are made, but often it seems that a backward step is being taken. In spite of all these facts the relating of lenses to the types mentioned is the best and easiest way of classifying them.

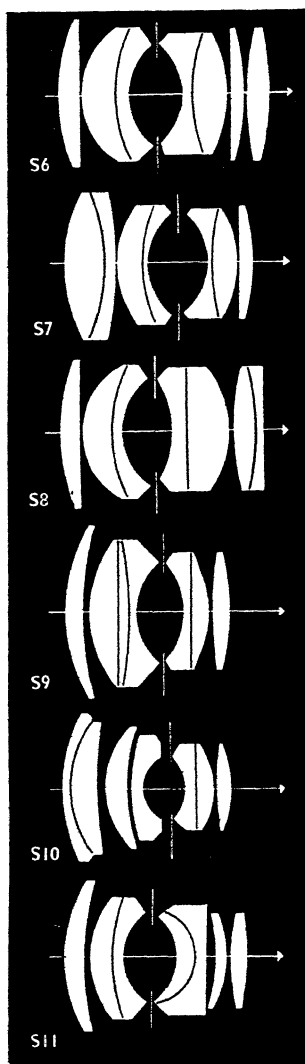
The simplest form of symmetrical lens is the rapid-rectilinear already described. The earliest development of this type into a lens approaching the modern standard of performance was made when new glasses were discovered at Jena towards the end of last century. In fact it was only the discovery of these glasses that made possible the construction of a symmetrical anastigmat.

The great virtue of the symmetrical lens construction is the almost automatic correction for coma, distortion, and lateral chromatic aberration. One set of glasses really furnishes a lens with a stop behind it, and the other set a lens with a stop in front of it. Each of these contributes coma, distortion, and lateral chromatic aberration of the same amount but of opposite signs or directions, provided—and it is an important proviso—that the object and its image are at the same distance from the lens, as happens in full-size copying work. When the lens is used with the object at a considerable distance from the lens as is normal in photographic work this automatic balancing of aberrations is no longer obtained. But the lack of balancing that is now introduced is not responsible for more than a trace of any of these aberrations appearing in the lens. What coma, distortion and lateral colour are introduced by the change from copying to normal conditions can be removed by making slight changes to the curves of one set of glasses while retaining the other set unchanged. In the majority of the lenses mentioned below it will be taken for

The early form of symmetrical lens S1 is still made to-day as the *Ross Homocentric* and it has formed the basis of the wide angle lenses W2 and W4 shown on page 173. The well-known *Dagor* construction S2 has been elaborated by *Ross*, *Berthiot*, *Steinheil* and others in the form shown in S3. The form S4, for instance in the *Dallmeyer Speed Anastigmat* represents a more unusual variation of the symmetrical type. S5 indicates the construction of the *T.T. & H. Speed Panchro* lens which was introduced in 1920. This is the most important lens shown on this page and it has been adopted and elaborated by nearly all lens manufacturers in recent years. Some of its many variations are shown on following pages.



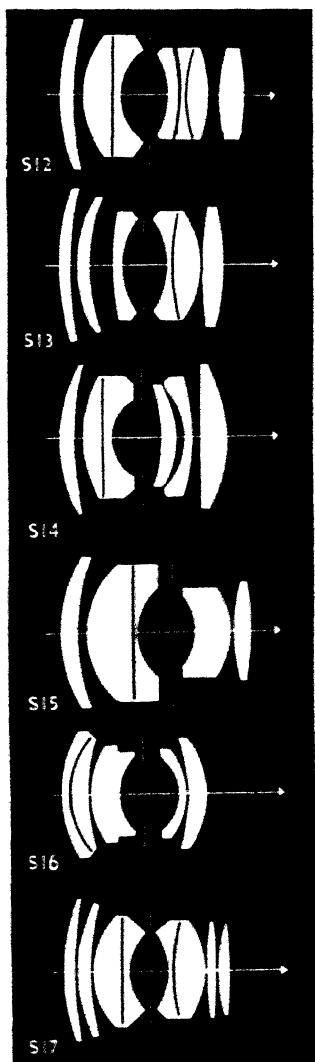
SYMMETRICAL LENSES



All these forms are direct derivatives from the Speed Panchro construction shown previously in S5. With the exception of S7 the relative apertures of these lenses have been taken to $f/1.4$ or $f/1.5$. Examples are the *Leitz Summarit* (S6), the *Kodak Cine Ektar* (S8), the *Dallmeyer Septac* (S9), the *Voigtlander Nokton* (S10) and the *Leitz Summarer* (S11). S7 shows the shape of the *Leitz Summaritar* and more recently the front two pairs of elements of this lens have been uncemented and all curvatures amended. This modification has been introduced by *Leitz* in their *Summicron* lens.

SYMMETRICAL LENS DERIVATIVES

Further elaboration from the basic Speed Panchro construction leads to designs like the *Berthiot Cinor* (S12), *Voigtlander Ultron* (S13), *Meyer Makro-Plasmat* (S14), *Wray Unilite*, *Zeiss Biometar* (S15), *Zeiss Planar* (S16), and the *Angenieux f0.95 cine lens* (S17). Some of these indicate the advantages of surface treatment to reduce reflection and loss of light at glass-to-air surfaces. Many of these constructions and those on other pages of this section rely on the increased number of such surfaces to achieve improved performance. Useful light transmission and freedom from flare characteristics can only be obtained by means of this coating technique.



SYMMETRICAL LENS DERIVATIVES

granted that this change has been made even if it is not specifically referred to, and since it does not appreciably upset the symmetry of the constructions they will still be referred to as symmetrical lenses, although in fact they depart slightly from this precise balancing.

When new optical glasses were introduced in Germany at the end of the last century it became possible to correct the field curvature of the Rapid Rectilinear type of lens. Unfortunately, the glass characteristics which permitted this correction prevented the correction of spherical aberration, and relative apertures therefore had to be severely restricted in these early anastigmats. Simultaneous correction of field curvature and spherical aberration was achieved by a combination of the old and new glasses in more complicated systems in which the two doublets of the Rapid Rectilinear type were each replaced by triplet, quadruplet or even quintuplet combinations. Many of these forms were developed in Germany and they have become known as the Continental Type. Although spherical aberration was corrected in these forms, residual zonal spherical aberration still limited relative apertures to about $f5.6$. Variations of these forms in use as wide-angle, convertible and process lenses are described in later sections.

Ross Homocentric: This lens can be regarded as a logical development from the Rapid-Rectilinear or R.R. lens already described. The lenses which previously were cemented together in the R.R. lens are now separated from one another and their order interchanged. The curves which had to be the same in the R.R. so that the glasses could be cemented together may now be different. Greater freedom is allowed to the designer, and advantage has been taken of this to produce an anastigmat with a vastly better field-curvature and astigmatism correction than that of any R.R. lens, while at the same time a comparatively small amount of zonal spherical aberration remains in the lens. The construction is shown on p. 153 diagram S1. Although the construction of this lens approximates to that of one of the wide-angle lenses described later, the *Homocentric* is not a

true wide-angle lens. Some covering power has been sacrificed to obtain the quality of performance over a more restricted field. In spite of this the lens has a covering power rather larger than a number of lenses based on other designs, and with the conventional size of plate, with a diagonal equal in length to the focal length of the lens, it is very suitable for use with a rising camera front. A virtue of this lens, as of many others of symmetrical construction, is that either half can be used alone with a small stop to give a lens of greater focal length. The corrections are well-maintained down to small distances of the object so that the lens is quite suitable for enlarging purposes.

T.T. and H. Speed-Panchro: The *Speed-Panchro* type of *Taylor, Taylor and Hobson*, introduced in 1920, played a great part in ushering in the era of really fast lenses. While not exactly a symmetrical lens it possesses a high degree of symmetry. The construction is shown in diagram S5 on p. 153. It can be regarded as derived from a symmetrical lens with three glasses in each cemented group, from each group of which a pair of cemented glasses have been separated and the curves then changed. The aperture of this lens as first designed was $f2$. The *Zeiss Biotar* lens is also of this construction, as are many other important makes of $f2$ lenses. The development of this basic construction can be classed as one of the major advances of the last twenty years. The especial virtue of such a type of lens is that it allows of a really beautiful central definition, following from the fine correction of the zonal spherical aberration and sphero-chromatism, i.e., variation of spherical aberration with the colour of the light.

With regard to this lens it is important to notice that two quite distinct types are made. One is intended specifically for 35 mm. film work and the astigmatism, coma, etc., are corrected for this region without reference to what happens beyond it. The other is intended for normal photographic use in which the diagonal of the plate is equal to the focal length. The two types are not interchangeable.

Lenses of this last type have been made with apertures

up to $f1.5$, and a development of this construction, in particular by *Taylor, Taylor and Hobson*, in which the back crown glass is split into two glasses has taken the aperture up to $f1.4$. There are other modifications of this design also to make it suitable for special jobs. For instance, in using such a construction in a projection lens for rear-projection in cinemas, the glasses that are usually cemented together are slightly separated and their curves changed to eliminate the chance of damage from the heat of the condensed arc light as explained previously.

The high degree of correction which is possible with the *Speed-Panchro* construction has provided a most useful basis for further development and part of this story is indicated on pp. 153-5 and in table XXIII on p. 159. It will be seen how the basic *Speed-Panchro* construction shown in diagram S5 on p. 153 has been amended in various ways to meet different conditions of use. In considering these, and variations of other types of lenses, it should be borne in mind that some of the variations are due to attempts on the part of manufacturers to evade patent protection. It does not follow that the most complicated lens is necessarily the best for any particular purpose. Whilst a large number of design variables can assist the designer to achieve a higher correction of aberration, the light loss and scatter due to thick components and a large number of glass-to-air surfaces can be quite serious.

To sum up what has been said about symmetrical lenses: the primitive types, developed as the first anastigmats towards the end of last century after the discovery of the new Jena glasses, and consisting of two groups of cemented glasses each with three to five components, are useful up to about $f5.6$. But they are apt to be rather too complicated where such a moderate aperture is required. The Homocentric achieves a useful standard of performance with only 4 glass elements. The Speed-Panchro takes the aperture to $f2$ or $f1.4$ and has formed the basis for further developments by a large number of manufacturers throughout the world.

XXIII.—SYMMETRICAL LENSES AND ALLIED TYPES

| <i>Maker</i> | <i>Name of Lens</i> | <i>Focus</i> | <i>Aperture</i> | <i>Field Covered</i> | <i>Diagram</i> (pp. 153-5) |
|------------------------|----------------------|--------------|----------------------------|----------------------|-------------------------------|
| <i>Agfa ...</i> | <i>Solagon</i> | 50 mm. | <i>f</i> 2 | 50° | S5 |
| <i>Angenieux ...</i> | — | 50 mm. | <i>f</i> 1.5, <i>f</i> 1.8 | 24 × 36 mm. | S5 |
| | — | 25 mm. | <i>f</i> 1.4 | 16 mm. cine | S5 |
| | — | 25 mm. | <i>f</i> 0.95 | 16 mm. cine | S17 |
| | — | 28-100 mm. | <i>f</i> 1.8 | 35 mm. cine | S5 |
| <i>B. & L. ...</i> | <i>Animar</i> | 15 & 25 mm. | <i>f</i> 1.5 | 8 & 16 mm. cine | S5 |
| <i>Berthiot ...</i> | <i>Orthor</i> | — | <i>f</i> 5 | 62° | S3 |
| | <i>Eurygraphe</i> | — | <i>f</i> 6.2 | 54° | S2 |
| | <i>Perigraphe</i> | — | <i>f</i> 6.8 | 65° | S2 |
| | <i>Flor</i> | — | <i>f</i> 2.8 | 45° | S5 |
| | <i>Flor</i> | — | <i>f</i> 1.5 | 45° | S6 |
| | <i>Cinor</i> | — | <i>f</i> 1.5 | 43° | S12 |
| <i>Canon ...</i> | <i>Canon</i> | 35-85 mm. | <i>f</i> 1.8-2.8 | 24 × 36 mm. | S5 |
| | <i>Canon</i> | 85 mm. | <i>f</i> 1.5 | 24 × 36 mm. | S9 |
| <i>Dallmeyer ...</i> | <i>SuperSix</i> | 1-8 in. | <i>f</i> 1.9 | 50° | S5 |
| | <i>Septac</i> | 2 in. | <i>f</i> 1.5 | 50° | S9 |
| | <i>Speed Anast.</i> | 0.6-3 in. | <i>f</i> 1.5 | 16 mm. cine | S4 |
| <i>Fuji ...</i> | <i>Fujinon</i> | 35 mm. | <i>f</i> 2 | 24 × 36 mm. | S6 |
| <i>Goerz ...</i> | <i>Dagor</i> | 1½-19 in. | <i>f</i> 6.8-7.7 | 56°-87° | S2 |
| <i>Kin-Optik ...</i> | <i>Erax</i> | 32 mm. | <i>f</i> 1.9 | 16 mm. cine | S5 |
| <i>Kodak ...</i> | <i>Cine Ektar</i> | 25 mm. | <i>f</i> 1.4 | 16 mm. cine | S8 |
| | <i>Retina-Xenon</i> | 50 mm. | <i>f</i> 2 | 24 × 36 mm. | S5 |
| <i>Leitz ...</i> | <i>Summaron</i> | 35 mm. | <i>f</i> 3.5 | 24 × 36 mm. | S5 |
| | <i>Summitar</i> | 50 mm. | <i>f</i> 2 | 24 × 36 mm. | S7 |
| | <i>Summicron</i> | 50 mm. | <i>f</i> 2 | 24 × 36 mm. | S7 |
| | <i>Summarit</i> | 50 mm. | <i>f</i> 1.5 | 24 × 36 mm. | S6 |
| | <i>Summarex</i> | 85 mm. | <i>f</i> 1.5 | 24 × 36 mm. | S11 |
| <i>Meyer ...</i> | <i>Doppel-anast.</i> | 180-240 mm. | <i>f</i> 6.8 | 64° | S2 |
| | <i>Makro-plasmac</i> | 105 mm. | <i>f</i> 2.7 | 43° | S14 |
| <i>Nippon ...</i> | <i>Nikkor</i> | 35 & 180 mm. | <i>f</i> 2.5 | 24 × 36 mm. | S5 |
| <i>Olympus ...</i> | <i>G. Zuiko</i> | 44 mm. | <i>f</i> 1.9 | 24 × 36 mm. | S8 |
| <i>Rodenst. ...</i> | <i>Heligon</i> | 35 & 50 mm. | <i>f</i> 2-2.8 | 24 × 36 mm. | S5 |
| | <i>Heligon</i> | 12.5-50 mm. | <i>f</i> 1.5-2 | 8 & 16 mm. cine | S5 |
| <i>Ross ...</i> | <i>Homocentric</i> | 7-12 in. | <i>f</i> 6.3 | 60° | S1 |
| | <i>Xtralux</i> | 2 in. | <i>f</i> 2 | 24 × 36 mm. | S5 |

| <i>Maker</i> | <i>Name of Lens</i> | <i>Focus</i> | <i>Aperture</i> | <i>Field Covered</i> | <i>Diagram (pp. 153-5)</i> |
|--------------|---------------------|--------------|-----------------|----------------------|--------------------------------|
| Schneider | Xenon | 13-80 mm. | f1.5-2 | 50° | S5 |
| | Xenogon | 35 mm. | f2.8 | 24 × 36 mm. | S5 |
| | Xenotar | 80-150 mm | f2.8 | 55° | S15 |
| Steinheil | Orthostigmat | 35 mm. | f4.5 | 64° | S3 |
| T.T. & H. | Speed-Panchro | 24-108 mm. | f2 | 35 mm. cine | S5 |
| | Deep F. | 4 in. | f2.5 | 35 mm. & 24 × 36 mm. | S5 |
| | Panchro | | | | |
| | Anastigmat | 2 in. | f2 | 24 × 36 mm. | S5 |
| | Double Sp. Panchro | 40, 50 mm. | f2 | 24 × 36 mm. | S5 |
| | hvtal | 1 in. | f1.4 | 16 mm. cine | S5 |
| Voigtland. | Ultron | 50 mm. | f2 | 24 × 36 mm. | S13 |
| | Nokton | 50 mm. | f1.5 | 24 × 36 mm. | S10 |
| Wollensak | Cine Raptar | 1-2 in. | f1.5 | 16 mm. cine | S5 |
| Wray | Unilite | 1½-5½ in. | f2 | 53° | S15 |
| | Cine Unilite | 1-4 in. | f1.9 | 35 mm. cine | S15 |
| Zeiss | Biometar | 35 mm. | f2.8 | 24 × 36 mm. | S15 |
| | Biotar | 25-58 mm. | f1.5-2 | 40° | S5 |
| | Planar | 80 mm. | f2.8 | 2½ × 2½ in. | S16 |

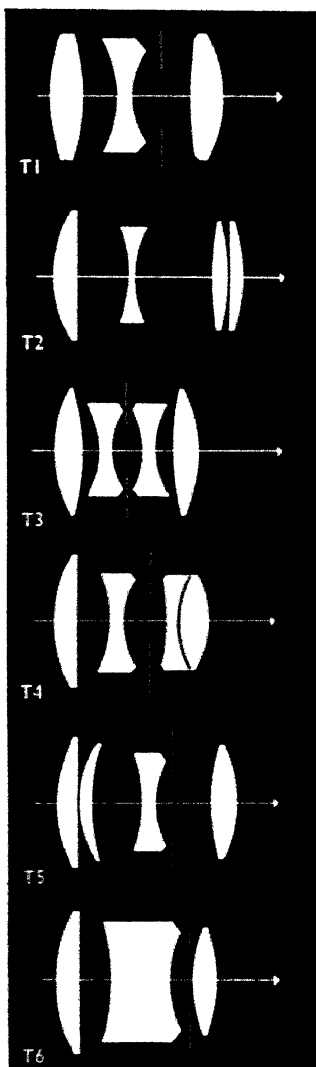
The Type of the Cooke Triplet

When H. D. Taylor developed his *Cooke Triplet* in 1893 a step was made of the greatest importance as far as the design and production of photographic lenses was concerned.

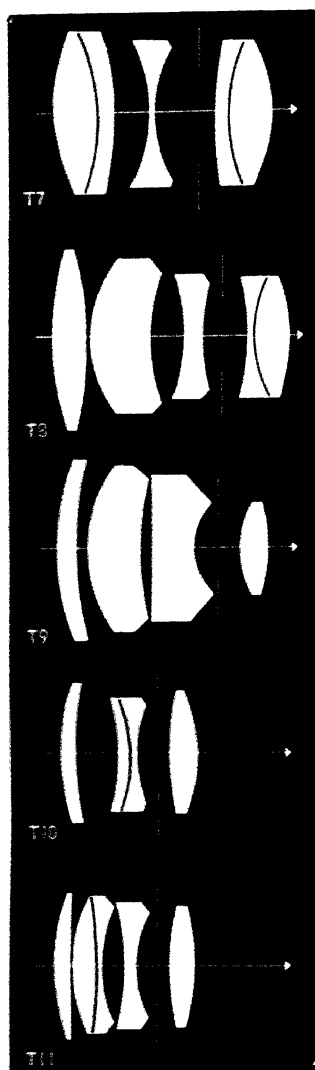
H. D. Taylor was with *Cooke and Sons* of York, now *Cooke, Troughton and Simms*, when the lens was designed, and it was produced by *Taylor, Taylor and Hobson* of Leicester under the name of the *Cooke lens*. An early form of this lens is shown on p. 161, diagram T1. It represented a complete break from existing tradition, as represented at that date by *Petzval* lenses and early symmetrical anastigmats.

H. D. Taylor tackled the problem of field curvature from an entirely new point of view. He found that the curvature could be removed by utilising a collective lens element

Diagram T1 illustrates one of the original Triplets invented by Dennis Taylor at the turn of the century. This development was perhaps the most important in the history of the photographic lens and many of these original forms are still in widespread use to-day. The next four diagrams show how this basic form has led to other designs in which the single elements of the triplet have been replaced by pairs of elements or by more complicated compound components. T6 indicates the use of unusually thick lens elements. T4 is the well-known *Tessar* construction now adopted by nearly all lens manufacturers.

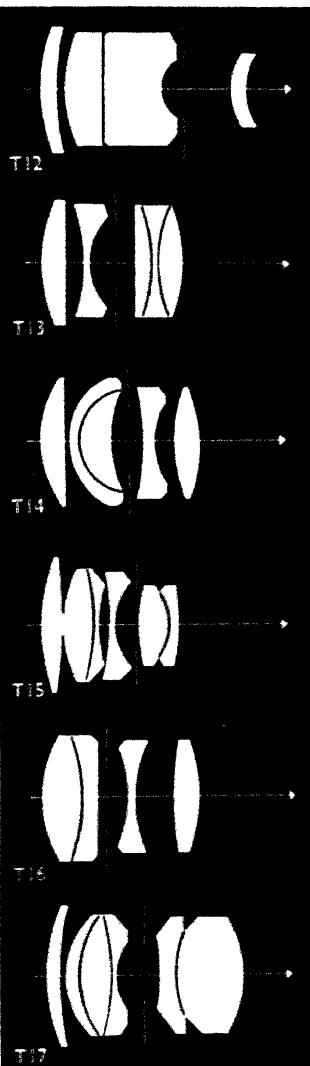


THE COOKE TRIPLET TYPE OF LENS

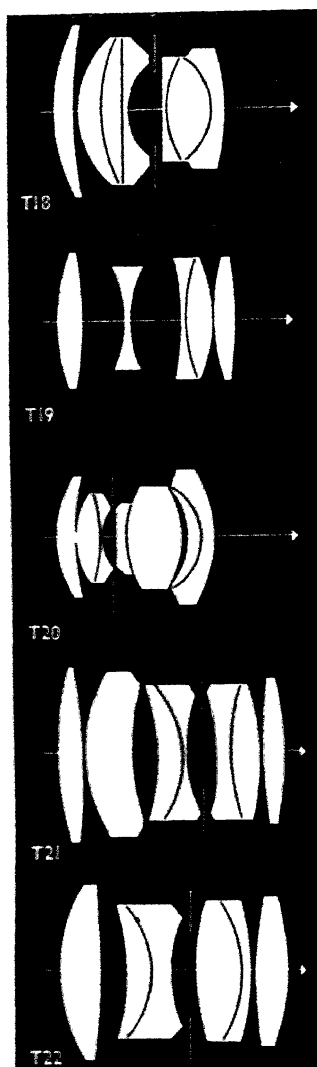


More elaborate developments from the triplet form include the *Dallmeyer Pentac*, certain *Kodak Ektars*, the *Color-Heliar* (T7); certain *Schneider Xenars*, the *Steinheil Quinar* (T8); the *T.T. & H. Ivtal* (T9), the *Leitz Hektor* (T7 and T10), and others. These variations, some permitting apertures of $f/1.4$, emphasise the importance of this family of lenses.

DERIVATIVES OF THE TRIPLET LENS



The constructions on this page continue the story of the triplet family. T17 is the well-known *f*2 Sonnar in which the space between a front pair of collective elements and the central dispersive element has been filled by a glass of low refractive index. The resultant reduction in the number of glass to air surfaces was of great advantage before the days of surface treatment.



The $f1.5$ Sonnar shown in T18 follows from T17 and illustrates how the change from a doublet rear component to a triple component has permitted the wider aperture of $f1.5$. T20, as used in the *Biogon*, belongs to the same sub-division of this triplet group and is noteworthy for its combined wide field of view and wide relative aperture.

MORE COMPLEX TRIPLET DERIVATIVES



T23



T24



T25



T26

Japanese lens designers have produced a number of further variations as shown in T23 to T25. These employ special high-refractive glasses and in this way achieve particularly wide apertures; the most spectacular example is the *Fujinon f1.2*, T23. The *T.T. & H. Tele-Panchro*, T26, also follows this trend with a long-focus lens.

MORE COMPLEX TRIPLET DERIVATIVES

and a dispersive lens element separated from one another. Furthermore, by splitting the collective element into two parts and placing a collective element either side of a central dispersive element, he had just sufficient variables to permit correction of all the other aberrations.

The earlier forms of *Cooke Triplet* had apertures up to about $f6.3$. Modern types are made with apertures up to $f3$ in moderate focal lengths, and up to $f2.5$ in focal lengths of 1 inch and less such as are used in small movie cameras. They are essentially normal lenses and just suffice to cover a plate with a diagonal equal to the focal length.

Prior to the invention of the *Speed-Panchro* lens (p. 157) the *Cooke Triplet* formed a much better basis for further development than the early forms of symmetrical lenses.

The single components of the *Triplet* can be replaced by compound cemented components or by pairs of similar components. The lens diagrams on pp. 161-5 will give an indication of the present state of the art and the way in which this form has been modified to provide improved performance at wider apertures. An arbitrary choice must be made in mentioning some of the better-known variants.

Tessar Lens: One of the earliest important variations of the *Triplet* was the *Tessar* lens exploited so well by Zeiss and produced, with minor modifications, by nearly every lens manufacturer. The *Tessar* is shown in diagram T4 on p. 161 and contains a cemented doublet in place of the rear component of the *Triplet*. The *Tessar* construction naturally affords better definition than the *Cooke Triplet* construction over the same field, as the slightly more complicated (and more expensive) construction gives the designer greater liberty and a more delicate control in correcting the aberrations. Present-day apertures extend up to about $f2.8$, with excellent definition and a rather flatter field than the *Cooke Triplet* type of the same aperture. Up to apertures of about $f5.6$ the use of a *Tessar* construction is somewhat of a luxury. Beyond about $f4.5$ the *Tessar* construction is to be preferred if the extra expense is warranted by the higher standard of definition afforded.

In many cameras with between-lens shutters of the *Compur* type and carrying lenses of *Tessar* or *Triplet* construction, expensive focusing mechanisms have been avoided by not moving the lens as a whole but by changing its focal length. The separation between the first and second components is increased slightly and this in turn decreases the focal length. Inevitably there is a certain loss of definition consequent upon altering the separation of the glasses. But by skilful design these changes of definition can be kept within reasonable limits, and are not unduly troublesome in the actual use of the lens. Generally the lens is adjusted on the camera in such a way that the separation yielding best definition will focus objects at a medium distance. This ensures that focusing for infinity or very short distances does not demand considerable variations from the ideal separation.

The *Pentac* lens developed by *Dallmeyer* and since modified by other manufacturers is shown in diagram T7 on p. 162. It is a variation in which both collective components are cemented doublets.

Diagrams T5, T3 and T2 on p. 161 show variations in which the first, second and third components respectively have been split up into a pair of similar components. The first variation yields apertures up to $f1.9$ covering the comparatively narrow fields of view needed for cinematography. The second, first introduced as the *Aviar* lens of *Taylor*, *Taylor and Hobson*, covers a plate diagonal slightly larger than the focal length at an aperture of $f4.5$. The third variation provides apertures up to $f2.5$ covering a plate diagonal rather less than the focal length.

For some purposes, particularly among the faster lenses, the two lines of development, building up a component into a cemented group of lens elements and splitting up a component into two single lens elements, are combined in one lens. Several of these variations are shown on pp. 163–5. In the case of the *Zeiss Sonnar* lenses (diagrams T17 and T18 on pp. 163–4), the rear component of the *Triplet* has been replaced by a cemented group of lenses; the front component

has been split into two single collective components and the space between the second front component and the central dispersive component has been filled with a glass of low refractive index.

To sum up what has been said about the Cooke Triplet and its allied types; up to apertures of about $f6.3$, and over normal fields where the diagonal of the plate covered is equal to the focal length of the lens, the simple Triplet form is quite adequate in the vast majority of cases. The Triplet can also be used up to apertures of about $f2.8$, especially in short focal lengths covering narrow fields, and up to $f2.5$ in very short focal lengths suitable for 8 and 9.5 mm. movie cameras. In the region of $f4.5$ or $f5.6$ and upwards a better performance is afforded by using either the Tessar or Aviar form although this type is naturally more expensive. Above $f2.5$ constructions vary quite considerably according to the field of view and other factors and no hard and fast rules can be laid down.

XXIV.—COOKE TRIPLET LENSES AND ALLIED TYPES

| Maker | Name of Lens | Focus | Aperture | Field Covered | Diagram (pp. 161-5) |
|---------------|--------------|-------------------------|------------|----------------------------------------|------------------------|
| Agfa ... | Agomar | 100-150 mm. | $f2.8-3.2$ | — | T1 |
| | Agnar | 85-105 mm. | $f4.5-6.3$ | 56° | T1 |
| | Apotar | 50-105 mm. | $f3.5-4.5$ | 56° | T1 |
| | Sollmar | 50-105 mm. | $f2.8-4.5$ | 56° | T4 |
| | Kine-anast. | 12 mm. | $f2.8$ | 8 mm. cine | T1 |
| Agilux ... | — | 80 mm. | $f2.8$ | $2\frac{1}{2} \times 2\frac{1}{2}$ in. | T4 |
| | — | 90 mm. | $f4.5$ | $2\frac{1}{2} \times 2\frac{1}{2}$ in. | T1 |
| Aldis ... | Anastigmat | 1.4-2 in. | $f3$ | — | T1 |
| | Projection | 4 - $18\frac{1}{2}$ in. | $f2.8-4.5$ | — | T1 |
| | — | 50 mm. | $f2.5$ | 24×36 mm. | T2 |
| | — | 85 mm. | $f2.5$ | 24×36 mm. | T1 |
| Angenieux ... | — | 75 mm. | $f2.5$ | 16 mm. cine | T11 |
| | — | 90-135 mm. | $f1.8-2.5$ | 24×36 mm. | T11 |
| | — | 90-135 mm. | $f2.5-3.5$ | 24×36 mm. | T5 |
| B. & L. ... | Animar | 12.5-50 mm. | $f2.5-3.5$ | 8 & 16 mm. cine | T1 |
| | Animar | 14-26 mm. | $f1.9$ | 8 & 16 mm. cine | T3 |
| | Animar | 75-100 mm. | $f3.5$ | 16 mm. cine | T5 |

| <i>Maker</i> | | <i>Name of Lens</i> | <i>Focus</i> | <i>Aperture</i> | <i>Field Covered</i> | <i>Diagram</i> (pp. 161-5) |
|--------------|-----|---------------------|--------------|-----------------|----------------------|-------------------------------|
| Berthiot | ... | Olor | — | f5.7-6.8 | 60° | T13 |
| | | Flor | — | f4.5 | 58° | T13 |
| | | Flor | — | f3.5 | 56° | T4 |
| | | Cinor | — | f1.9 | 27° | T2 |
| | | Cinor proj. | — | f1.8 | 41° | T19 |
| | | Stellor | — | f3.5 | 40° | T1 |
| Canon ... | ... | Canon | 50 mm. | f3.5 | 24 × 36 mm. | T4 |
| | | Canon | 50 mm. | f1.5 | 24 × 36 mm. | T18 |
| | | Canon | 100 mm. | f3.5 | 24 × 36 mm. | T25 |
| | | Canon | 135 mm. | f3.5 | 24 × 36 mm. | T12 |
| Dallmeyer | ... | Triple anast. | 0.6-3 in. | f2.9 | 8 & 16 mm. cine | T1 |
| | | Projection | 3-6 in. | f3.5-4.5 | 24 × 36 mm. | T1 |
| | | Epidiascope | 12-24 in. | — | 3½ × 3½ in. | T1 |
| | | Serrac | 1½-18 in. | f4.5 | 53° | T4 |
| | | Perfac | 6-30 in. | f6.3 | 53° | T4 |
| | | Dalmac | 1½-15 in. | f3.5 | 50° | T4 |
| | | Pentac | 3-12 in. | f2.9 | 50° | T7 |
| Fuji ... | ... | Fujinon | 50 mm. | f1.2 | 24 × 36 mm. | T23 |
| Goerz ... | ... | Dogmar | 3½-12 in. | f4.5 | 48°-55° | T3 |
| Kern ... | ... | Yvar | 13-150 mm. | f1.9-4 | 8 & 16 mm. cine | T6 |
| | | Cine Switar | 13-25 mm. | f1.4, 1.5 | 8 & 16 mm. cine | T22 |
| | | Photo Switar | 50 mm. | f1.8 | 24 × 36 mm. | T21 |
| Kliffitt ... | ... | Makro-Kilar | 40 mm. | f2.8 | 24 × 36 mm. | T4 |
| | | Kilar | 90 mm. | f2.8 | 24 × 36 mm. | T4 |
| | | Kilar | 135 mm. | f3.8 | 24 × 36 mm. | T1 |
| | | Kilar | 150 mm. | f3.5 | 24 × 36 mm. | T1 |
| | | Grand-Kilar | 180 mm. | f1.9 | 24 × 36 mm. | T5 |
| Kodak | ... | Anastar | 2-4 in. | f4.5 | 53° | T4 |
| | | Ektar | 8½-14 in. | f6.3 | 53°-64° | T4 |
| | | Ektar | 8 in. | f7.7 | 56° | T3 |
| | | Ektar | 105 mm. | f3.7 | 52° | T7 |
| | | Ektar | 4-6 in. | f4.5 | 56° | T4 |
| | | Ektar | 4 in. | f3.5 | 52° | T7 |
| | | Anastar | 80 mm. | f3.5 | 52° | T5 |
| | | Ektar | 44 mm. | f3.5 | 52° | T4 |
| | | Anaston | 105 mm. | f4.5, 6.3 | 52° | T1 |
| Leitz ... | ... | Hektor | 135 mm. | f4.5 | 24 × 36 mm. | T10 |
| | | Elmar | 50, 90 mm. | f3.5, 4 | 24 × 36 mm. | T4 |
| | | Hektor | 28 mm. | f6.3 | 24 × 36 mm. | T7 |

| <i>Maker</i> | | <i>Name of Lens</i> | <i>Focus</i> | <i>Aperture</i> | <i>Field Covered</i> | <i>Diagram (pp. 161-5)</i> |
|------------------|-----|---------------------|--------------|-----------------|----------------------|--------------------------------|
| <i>Meyer ...</i> | ... | Trioplan | 50-360 mm. | f2.8-4.5 | 24°-60° | T1 |
| | | Primotar | 85-180mm. | f3.5 | 26°-52° | T4 |
| | | Primoplan | 58-75 mm. | f1.9 | 32°-41° | T14 |
| | | Helioplan | 40 mm. | f4.5 | 56° | T3 |
| <i>Nippon</i> | ... | Nikkor | 35 mm. | f3.5 | 24 × 36 mm. | T4 |
| | | Nikkor | 50 mm. | f3.5 | 24 × 36 mm. | T4 |
| | | Nikkor | 50 mm. | f1.4 | 24 × 36 mm. | T18 |
| | | Nikkor | 50 mm. | f2 | 24 × 36 mm. | T17 |
| | | Nikkor | 85 mm. | f1.5 | 24 × 36 mm. | T18 |
| | | Nikkor | 85 mm. | f2 | 24 × 36 mm. | T24 |
| | | Nikkor | 105 mm. | f2.5 | 24 × 36 mm. | T24 |
| | | Nikkor | 135 mm. | f3.5 | 24 × 36 mm. | T12 |
| | | Nikkor | 250 mm. | f4 | 24 × 36 mm. | T12 |
| | | Nikkor | 500 mm. | f5 | 24 × 36 mm. | T1 |
| <i>Olympus</i> | ... | D Zuiko | 45 mm. | f3.5 | 24 × 36 mm. | T4 |
| | | E Zuiko | 48 mm. | f2.8 | 24 × 36 mm. | T8 |
| <i>Redenst.</i> | ... | Trinar proj. | 50-100 mm. | f2.8-3.6 | 46°-56° | T1 |
| | | Splendon proj. | 200-600 mm. | f3.5-10.5 | 12°-38° | T1 |
| | | Ysar | 50-420 mm. | f3.5, f4.5 | 50°-55° | T4 |
| | | Eurymar | 180-300 mm. | f4.5 | 55° | T3 |
| | | Trinar | 35-105 mm. | f2.9-4.5 | 50°-55° | T1 |
| | | Ronar | 10, 12.5 mm. | f1.9 | 8 mm. cine | T5 |
| | | Euron | 38, 75 mm. | f2.8, 3.5 | 8 & 16 mm. cine | T1 |
| <i>Ross ...</i> | ... | Xpres | 6-14 in. | f3.5-4.5 | 58° | T4 |
| | | Xtralux | 135 mm. | f4.5 | 24 × 36 mm. | T4 |
| | | Xtralux | 90 mm. | f3.5 | 24 × 36 mm. | T4 |
| | | Rosstar | 75 mm. | f4.5 | 55° | T4 |
| <i>Schneider</i> | ... | Kinoplan | 12.5 mm. | f2.7 | 8 mm. cine | T1 |
| | | Xenar | 38-480 mm. | f3.5-4.5 | 52° | T4 |
| | | Xenagon | 35 mm. | f3.5 | 24 × 36 mm. | T4 |
| | | Radionar | 38-135 mm. | f2.9-4.5 | 52° | T1 |
| | | Xenoplan | 13 mm. | f1.9 | 8 mm. cine | T5 |
| | | Xenar | 38-105 mm. | f2.8 | 52° | T8 |
| | | Isogon | 40 mm. | f4.5 | 24 × 36 mm. | T3 |
| | | Tele-Xenar | 75-135 mm. | f3.5 | 24 × 36 mm. | T12 |
| <i>Steinheil</i> | ... | Cassar | 36-105 mm. | f2.8-6.3 | 52° | T1 |
| | | Quinon | 50 mm. | f2 | 50° | T17 |
| | | Quinar | 135 mm. | f2.8 | 18° | T8 |
| | | Culminon | 150-210 mm. | f4, 4.5 | 55° | T4 |
| | | Cassarion | 40 mm. | f3.5 | 56° | T1 |
| | | Culminar | 135 mm. | f4.5 | 56° | T4 |
| | | Culminar | 85 mm. | f2.8 | 28° | T16 |

| <i>Maker</i> | | <i>Name of Lens</i> | <i>Focus</i> | <i>Aperture</i> | <i>Field Covered</i> | <i>Diagram (pp. 161-5)</i> |
|----------------------|-----|-------------------------|--------------|-----------------|----------------------|--------------------------------|
| <i>T.T. & H.</i> | ... | Aviar II, IIIb | 6-15 in. | f4.5, 6 | 52° | T3 |
| | | Adotal | 80 mm. | f2.8 | 2½ × 2½ in. | T11 |
| | | Ivotal | 2-3 in. | f1.4 | 8 & 16 mm. cine | T9 |
| | | Myta | 0.5, 0.7 in. | f2.5 | 8 & 16 mm. cine | T2 |
| | | Serital | 1 in. | f1.9 | 8 & 16 mm. cine | T5 |
| | | Teletal | 2, 2.8 in. | f2.8, 3.5, | 8 & 16 mm. cine | T1 |
| | | Taytal | 0.5 in. | f1.7 | 8 mm. cine | T5 |
| | | Double Speed Panchro | 75 mm. | f2 | 24 × 36 mm. | T15 |
| | | Tele-Panchro | 6 in. | f2.8 | 24 × 36 mm. | T26 |
| <i>Voigtland.</i> | ... | Color Skopar | 55-165 mm. | f3.5, 4.5 | 55°-60° | T4 |
| | | Color Heliar | 75-105 mm. | f3.5 | 2½ × 2½ in. | T7 |
| | | Apo-Lanthar | 105-300 mm. | f4.5 | 55° | T7 |
| <i>Woffensak</i> | ... | Raptar | 2-12 in. | f4.5 | 50°-56° | T4 |
| | | Cine Raptar | 0.7-1½ in. | f2.5-3.5 | 8 & 16 mm. cine | T1 |
| | | Cine Raptar | 1-2 in. | f1.9 | 16 mm. cine | T2 |
| | | Cine Raptar | 1½-3 in. | f2.5 | 8 & 16 mm. cine | T5 |
| <i>Wray</i> ... | ... | Super | 2-7 in. | f3.5, 4.5 | 46°-52° | T1, T4 |
| | | Lustrar | 5½-15 in. | f4.5 | 52°-70° | T3, T4 |
| | | H.R. Lustrar | 8 in. | f8 | 4½ × 6½ in. | T4 |
| | | Lustrar | 35 mm. | f3.5 | 24 × 36 mm. | T4 |
| | | Unilux | 50 mm. | f2.8 | 24 × 36 mm. | T5 |
| | | Lustrar | 90 mm. | f4 | 24 × 36 mm. | T16 |
| <i>Zeiss</i> ... | ... | Triotar | 75-135 mm. | f3.5, 4 | 33°-60° | T1 |
| | | Tessar | 37.5-300 mm. | f2.8-6.3 | 44°-62° | T4 |
| | | Sonnar | 50, 85 mm. | f2 | 24 × 36 mm. | T17 |
| | | Sonnar | 50 mm. | f1.5 | 24 × 36 mm. | T18 |
| | | Sonnar | 135-300 mm. | f4 | 24 × 36 mm. | T12 |
| | | Biogon | 35 mm. | f2.8 | 24 × 36 mm. | T20 |

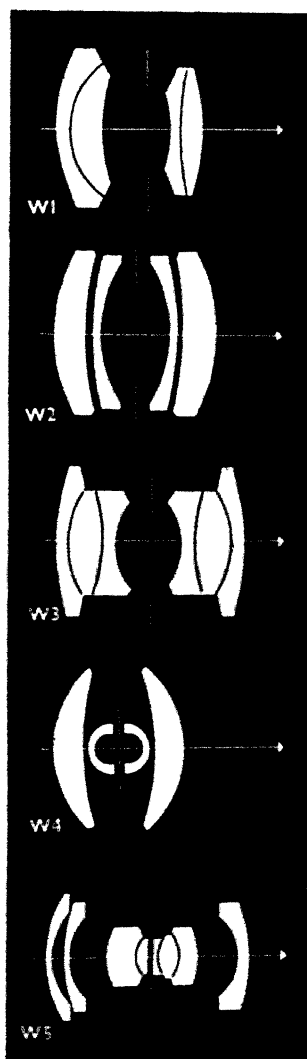
Wide-Angle Lenses

What can be regarded as the normal field for a photographic lens to cover is a plate with a diagonal equal to the focal length of the lens. This means that the angle of the field is about 53°. Any lens covering a field appreciably greater than this, say 65° or a diagonal about $1\frac{1}{2}$ times the focal length, can be classed as a "wide-angle lens." Fields covered by wide-angle lenses go up to about 100°, or a plate diagonal about 2.4 times the focal length of the lens, and it is mainly the type of lens giving this covering power that is described by the term "wide-angle."

The most important field of application of wide-angle lenses is one in which the restrictions of space are most strongly felt, namely interior photography of buildings. With the normal lens only a restricted field can be taken with the distance between camera and subject permitted in indoor work. The extra field covered by the wide-angle lens is invaluable here.

The value of wide-angle lenses from the point of view of their providing artistic or flattering studies in indoor photography belongs to works on the aesthetic side of photography. All that can be noted here is that the wide-angle lens used in architectural work gives an impression of spaciousness not obtained with a normal angle of view. The effect is largely psychological.

Practically all modern wide-angle lenses are derived from the early types of symmetrical lenses described before (p. 152). The simplest wide-angle, one produced by several manufacturers, is shown in diagram W2 on p. 173. With this lens the focusing is done, as far as any visual focusing on a screen is concerned, with the lens at an aperture of about f6.3 to f7.7. The definition in the field at this aperture is quite good enough for composing the picture on a focusing screen but not quite good enough for photographic work. The light patch away from the centre of the negative consists of a hard bright core with a coma tail or halo sufficiently intense to print on the plate. The focusing is best done then



These lens forms are useful when wide-angle fields of view are required. The symmetrical type of lens is usually adopted for this purpose and the diagrams S2 and S3 under the symmetrical type group (p. 153) are also widely used.

WIDE-ANGLE LENSES

at or near to the centre of the negative where these light flairs are not pronounced. The actual exposure is taken at $f11$, at $f16$, or smaller apertures. When the lens is stopped down to this aperture the tails of light disappear and only the hard and compact core of light remains to be recorded on the plate. The point of making the aperture for focusing $f6.3$ in place of $f11$ or $f16$ is to make the focusing and composing more easy and accurate. Focusing by the light transmitted through a lens at $f16$ is not always an easy job. As a rule with this type of lens the field covered is rather larger at $f32$ than at $f16$, say 100 degrees compared with 90 degrees, and if a rising front is to be used the smaller aperture should be employed.

Higher Aperture Lenses: Such lenses are useful when it is possible to make a moderately long exposure, or to bring up batteries of photo-floods and so on. But for other classes of work where a wide-angle lens is needed, where a reasonable field has to be covered under cramped conditions with poor lighting, and where a short exposure is needed as in aerial photography a wider aperture is needed, up to about $f4$.

The diagrams referred to in table XXV on p. 176 will indicate the general construction of some of these wider apertured wide-angle lenses. In addition to the lenses generally available, a number of wide-angle lenses have been developed by various firms for special purposes. These include variations of the lens form shown in diagram W4 on p. 173 in which angular fields up to 100 degrees at apertures of about $f6$ have been achieved whilst maintaining the high standard of performance required by aerial survey work.

For the 24×36 mm. format there are a variety of wide-angle and semi wide-angle lenses. Many of these have been included in the preceding tables and diagrams.

Inverted Telephoto Wide-angle Lenses: The continued demand for wider aperture in wide-angle lenses has presented new problems, especially in lenses of short focal length. In many cases these problems have been solved by adopting the inverted telephoto construction which is described later (p. 205).

Depth of Field: There is one point that has to be mentioned specially in connection with wide-angle lenses, and that deals with orthodox depth of field calculations for this type. The basis of depth of field calculations has been given on pp. 65-8. What is frequently stated is that in the case of wide-angle lenses the hyperfocal distance calculated in the normal way can be divided by a factor. This factor is the ratio of the angle of view of the wide-angle lens to the angle of view of the normal photographic lens. With a photographic lens of normal angle about 50 degrees and a wide-angle covering about 100 degrees the factor mentioned can safely be taken as 2. That is, according to some statements the normal depth of field as on pp. 65-8 should be increased, since the hyperfocal distance there is to be halved for a wide-angle lens.

Whether it is justifiable to use this factor is quite another matter, and it should be examined in more detail to see exactly what it implies. The method worked out on pages 65-68 assumes that the negative is enlarged until when seen at the nearest distance of clear vision the perspective is just right. And it was pointed out there that the perspective point of view of the camera is the forward nodal point of the lens. None of these statements are invalidated because the lens happens to be a wide-angle lens. If the hyperfocal distance is halved, as is postulated by the method described above, this corresponds to viewing the enlargement at twice the distance needed to furnish a correct perspective. All that happens when this is done, apart from upsetting the perspective, is to make the angle subtended at the eye by the diagonal of the picture the same as that subtended by the diagonal of a picture taken with a normal lens, and viewed at the right distance to give the true perspective. There seems no valid reason why this should be done. A wide-angle lens is intended to see and record more than a normal lens, even if the picture as a whole seems larger than that given by a lens of normal focal length, with its narrower angle of view.

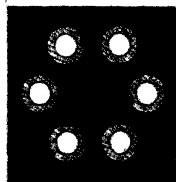
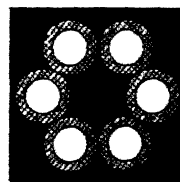
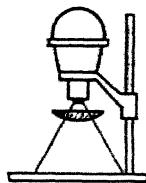
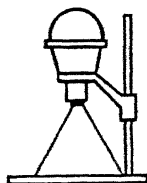
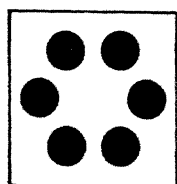
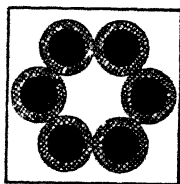
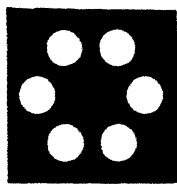
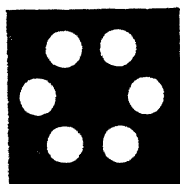
XXV.—WIDE-ANGLE LENSES

| Maker | Name of Lens | Focus | Aperture | Field Covered | Diagram (p. 173 also p. 153) |
|-----------|----------------------|-------------|----------|---------------|------------------------------------|
| Berthiot | ... Angulor | — | f3.3 | 72° | S5 |
| | ... Perigraphie | — | f14 | 90° | S2 |
| | ... Aquilor | — | f6.2 | 90° | W4 |
| Canon ... | ... Canon | 28 mm. | f3.5 | 24 × 36 mm. | S5 |
| Dallmeyer | ... Wide-angle | 2½–9 in. | f6.5* | 100° | W2 |
| Goerz ... | ... Rectagon | 3 in. | f6* | 90° | W2 |
| Kodak | ... Wide Field Ektar | 80–250 mm. | f6.3* | 75°–80° | W2 |
| Meyer ... | ... Aristostigmat | 100–160 mm. | f6.3* | 85° | W2 |
| Nippon | Nikkor | 25 mm. | f4 | 24 × 36 mm. | W4 |
| | Nikkor | 28 mm. | f3.5 | 24 × 36 mm. | S3 |
| Redenst. | ... Parigon | 90–130 mm. | f12 | 85° | W1 |
| Ross ... | ... W.A. Anst. | 5½–10½ in. | f16 | 100° | W1 |
| | ... W.A. Xpres | 4–20 in. | f4 | 70° | S3 |
| Schneider | ... Angulon | 65–210 mm. | f6.8 | 80°–105° | W3 |
| | ... Symmar | 135–360 mm. | f6.8 | 65°–80° | S2 |
| T.T. & H. | ... Series VIII | 3½–8½ in. | f6.5* | 90°–100° | W2 |
| | ... Pantal | 1.4–10 in. | f4 | 70° | S3 |
| Wray ... | ... W.A. Anst. | 3½ in. | f6.3* | 100° | W2 |
| Zeiss ... | ... Topogon | 25 mm. | f4 | 24 × 36 mm. | W4 |
| | ... Biogon | 21 mm. | f4.5 | 24 × 36 mm. | W5 |
| | ... Biogon | 38 mm. | f4.5 | 2½ × 2½ in. | W5 |

* For focusing only

Soft Focus Lenses

Portrait work, especially commercial or professional portrait work, is as much subtle flattery as photography. And among the things that can be controlled and chosen to produce a satisfying picture are lighting, camera angle and distance of the subject from the lens, focal length of the lens, and lastly the hardness of the lens definition.



The aim of any soft focus device is to give an image of a point consisting of a hard core and a tenuous halo. This softens the definition without giving an out-of-focus fuzzy effect (p. 178).

Left : Any soft focus device used on the camera will result in spreading the areas of light and the ultimate effect will be a lighter print.

Right : Any soft focus device used on the enlarger will result in spreading the shadows and the ultimate effect will be a darker print.

THE EFFECT OF SOFT FOCUS ATTACHMENTS.

The relation between the focal length of the lens and the perspective and modelling has already been discussed. The only thing that remains to be done is to give some account of the hardness of the lens definition.

Diffusion Discs : The aim of the lens designer and manufacturer is to produce a lens having at the same time needle sharp definition and a large aperture. This goes a long way towards satisfying the demands of the practical photographer who uses the lens. But there are times when really first class definition is considered to be a drawback, when a "better" pictorial result is sought with the help of a rather softer definition.

To get this softer definition either a specially designed lens has to be used (as dealt with below), or some device has to be used to soften the definition provided by a good modern lens.

One method of softening the definition is to move the lens or add a supplementary lens while the exposure is being made. The result of this is to superimpose a sharply defined picture on another that is out of focus and diffuse. Such a procedure is closely allied to that of obtaining increased depth of field, and has already been described on page 74.

Varlants of this method are to make two negatives, one sharply focused and the other out of focus and print one after the other on the one sheet of paper, or in making an enlargement to make part of the exposure with the enlarger focused sharply and part with the enlarger out of focus.

Another way of softening the focus is to use a "diffusion disc." The aim of such a disc is to scatter and disperse part of the light that enters the lens, so that after it has been refracted by the lens it forms a more or less tenuous veil of light round the proper image point. This gives a softening of the focus. It produces the same result in effect as that observed in the early morning when a thin mist is clearing away, and there seems to be a film of light over everything.

A diffusion disc may be used either in producing the negative or in making an enlargement. When it is used with a camera lens light is scattered from the highlights in the scene

Into the shadows, and an Impression of lightness is obtained. On the other hand when it is used in enlarging its function is to scatter light from the transparent parts of the negative, corresponding to the shadows of the original picture. Hence a *diffusion disc* (or for that matter a *soft focus lens* of the type described below) when used with a camera spreads light over the picture, when used with an enlarger it spreads shadow. The point is of æsthetic rather than optical interest.

One time-honoured method of procuring a diffusing disc or device in an enlarger is to put *thin chiffon* over the enlarging lens. This softens the definition of the enlargement. The softening is due to the operation of two factors : one is the reflection and scattering of the light that strikes the fibres of the chiffon, the other is the diffraction of the light that avoids the fibres (see pages 137-138). It is practically impossible to predict in advance the exact amount of diffusion that will be produced, and still less to judge whether it will be sufficient or not for the particular subject being dealt with.

Another method of introducing diffusion in an enlarger is to put a *sheet of ordinary window glass, of gelatine, or even of Cellophane* in front of the enlarger lens, between it and the enlarging easel.

The earliest method of introducing diffusion with a camera lens, was to use the shimmering effect produced by the *hot air rising from a gas flame*. It served all right with the rather long exposures then needed, but at the present time it is of hardly more than academic interest.

One method that has been used, although it is rather complicated and not particularly well adapted to use with panchromatic plates or films is to use a *plate of glass that actually consists of two glasses of different dispersions* (see page 96) *cemented together*, so that they upset the chromatic correction of the lens with which they are used.

Alternatively special diffusion discs are available from optical houses, which consist of *fine diamond lines ruled on optically polished glass*. These fit on to the front of the lens mount in the same way as a filter. The diamond rulings

scatter light into the parts of the image that would otherwise receive no illumination. In some cases the rulings are straight lines, but preferably they are concentric circles. In any case it is advisable to leave a clear central area so that if necessary hard definition can be obtained by stopping down the lens.

Incidentally it may be mentioned that many cheap filters are, involuntarily, excellent diffusion discs. This is true especially of the type consisting of gelatine between cover glasses, unless they are carefully made. A star test with a filter in front of the lens (as described on page 233) will show how a poor filter performs in this way.

Diffusing discs can be improvised in many ways. For instance a *disc of transparent plastic* such as Perspex can be covered with a multitude of fine scratches by rubbing it with a fine abrasive, and will then diffuse light. Alternatively a shallow pattern in relief can be embossed on the surface of such a material after softening it with hot water. Such a patterned surface will again diffuse light. A sheet of gelatine that has been slightly distorted by holding it in front of a fire will also diffuse light.

The principle to bear in mind in improvising a diffusing screen is that *a surface is to be produced which deviates slightly from perfect flatness in a fairly regular way*, either by having small scratches cut in it or by having a more or less even pattern cut in or formed on its surface. If a number of common transparent materials are examined by placing them in front of a lens in a star test (see page 233) it will be evident that in many cases the problem is not what will constitute an efficient diffusing disc, but rather what will transmit light without diffusing it slightly. The eye looks through only a small section of the transparent material at a time, corresponding to the diameter of the pupil of the eye which has a maximum value of about .2 inches. On the other hand the light incident on a lens comes as a rule through a much larger area, and the effects of slight imperfections in the material are more pronounced.

If a crude diffusion disc is to be improvised in a hurry an old plate from which the emulsion has been cleared can be

painted with a transparent varnish rather thickly and with a hard brush so that the brush marks are not removed.

Adjustable Diffusion Lenses : The alternative method of obtaining a diffused effect is to use a lens with a soft focus, and preferably one in which the softness of definition can be controlled. Of these lenses there are two types. In the first the definition has its maximum softness at full aperture, and is hardened by stopping the lens down. In the second type the definition at any aperture is under full control.

In either case the softness of focus is introduced by leaving more or less spherical aberration in the lens. With this spherical aberration every point on the plate is surrounded by a moderately diffuse halo, so that the hard contrast, obtained with a lens well-corrected for spherical aberration, is softened by the veil of light that this halo spreads over the edge of an image into its surrounding region. The effect is not the same as merely putting the lens out of focus, as this gives a light patch that is inclined to be of finite size but with an even distribution of light, so that the spread over of light is too severe and spoils the definition instead of softening it.

Focusing With Diffusion : Soft focus lenses are not a special type or types to be added to those already described. They are just existing types, mainly of Petzval, Cooke Triplet or Tessar form in which provision is made so that one or more of the glasses can be moved to introduce a variable amount of spherical aberration, or which are just lenses of these types with uncorrected spherical aberration. There is one point to notice, and that is the change in the position of the focus with any change in the amount of spherical aberration. Lenses of these types are always focused on a screen in the camera, and because of the fact just mentioned it is important that the focusing should be done with the iris aperture and amount of diffusion that are to be used in making the exposure.

Examples of the first type of soft focus lens are the Kodak f4.5 Portrait lenses and the Rodenstock Deep Field Imagon. These lenses are not well corrected for spherical aberration

at full aperture and the light patch consists of a halo round a hard core. When the aperture is cut down the halo is reduced until at about $f/16$ the definition is sharp.

Examples of the second type are the *Dallmeyer* and *Taylor*, *Taylor & Hobson Portrait Lenses* with apertures of $f/3.5$. In each of these the amount of spherical aberration can be controlled by separating some of the glasses and this determines the degree of diffusion given by the lens.

The following table indicates some of the lenses which have been designed specifically for portraiture. Many of the lenses described in other sections of this chapter are quite suitable for this purpose especially where a marked degree of softness is not required.

XXVI.—PORTRAIT AND SOFT FOCUS LENSES

| Maker | Name of Lens | Focus | Aperture | Field Covered | Diagram (p. 183 also p. 161) |
|-----------|-------------------------------------|-------------|--------------|-------------------------|------------------------------------|
| Berthiot | ... Stallor | — | $f/3.5$ | 40° | T1 |
| Dallmeyer | ... Portrait Anast. | 9–15 in. | $f/3.5$ | 50° | T4 |
| Kodak | ... Portrait Lens | 12–16 in. | $f/4.5$ | 48° | SF1 |
| Rodenst. | ... Deep Field Imagon Eurygon | 120–480 mm. | $f/4.5$ –5.8 | 20° – 40° | SF1 |
| | | 300–420 mm. | $f/4.5$ | 45° | T1 |
| T.T. & H. | ... Series BE | 10½–20 in. | $f/4.5$ | 44° – 50° | T1 |
| Wray | Portrait Anast. | 8½–14 in. | $f/3.5$ | 40° | T1 |

Enlarging and Process Lenses

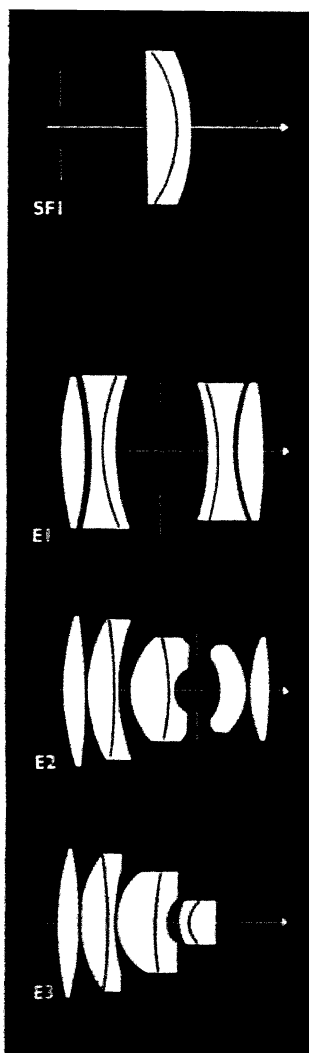
With enlarging and process lenses there is no need for a large aperture. But on the other hand a very high standard of performance is demanded.

The chromatic aberrations, astigmatism and curvature of field must be specially well corrected, although that is not to say that any slackening of performance can be tolerated as far as other aberrations are concerned. In some cases

SF1 illustrates a lens developed for portraiture in which the aberrations are not completely corrected at full aperture and thus provide the softness of definition which is often desirable in this class of work.

Many process lenses are based on some of the triplet and symmetrical forms illustrated on previous pages. The diagram E1 shows one form of process lens not included under these headings.

E2 and E3 illustrate the special copying lenses described on page 184.



the correction of camera lenses under enlarging conditions is sufficiently good for them to be used, but for the best performance a specially designed enlarging lens is desirable.

There are two major differences between enlarger and camera lenses from the aberrational point of view.

Firstly, the monochromatic aberrations described in a previous chapter vary with object and image conjugate distances. The extent of the variation will depend on the construction of the lens. But in nearly all cases a lens corrected for very distant objects cannot remain well corrected when it is used in an enlarger especially at low magnification factors.

Secondly, the spectral sensitivity of most printing papers demands best performance in the blue end of the spectrum whereas camera lenses intended for use with panchromatic emulsions may not yield their best definition in that region.

A feature that adds to the usefulness of enlarging lenses is a clicking arrangement on the iris control so that it is possible to know the lens aperture without fumbling in the dark or switching on dark-room lights. As the iris aperture passes through its successive stages a definite click is heard or felt and the aperture is known at once by counting the clicks.

Copying lenses are usually special types of enlarging lenses which have been designed to give a high standard of performance over a more restricted range of working conditions. These include the special extreme wide aperture lenses manufactured by *Taylor*, *Taylor & Hobson* and *Wray* for radiographic purposes where the magnification between object and image remains constant, and also the *Wray* f1 lens for copying oscillograph traces at a reduction of 4 : 1 on to 35 mm. film. Many lenses which can be classified as copying lenses are usually designed and made for one specific purpose and may not be listed in manufacturers' publications. They are shown as E2 and E3 on p. 183.

Process lenses for half-tone, line and colour work have to yield a particularly high standard of performance. The large plate sizes which are necessary for this class of work, and

the fact that so far it has proved impossible to achieve the required standard with wide-angle lenses, demand the use of lenses with unusually long focal lengths. Fortunately, a high lens speed is not required and an adequate performance is usually provided at apertures of about $f/10$.

In this class of work the types of glasses must be carefully chosen to obtain a small secondary spectrum. For rigorous colour work an apochromatic correction is highly desirable.

XXVII.—ENLARGING AND PROCESS LENSES

| <i>Maker</i> | | <i>Name of Lens</i> | <i>Focus</i> | <i>Aperture</i> | <i>Field Covered</i> | <i>Diagram (p. 183 also p. 153)</i> |
|--------------|-----|----------------------|------------------------|-------------------|---------------------------------------|---------------------------------------------|
| Berthiot | ... | Flor Apographe | — — | $f/2.8$ $f/10$ | 45° 44° | S5 E1 |
| Dallmeyer | ... | Enlarging Anast. | 2-10 in. | $f/3.5-5.6$ | 55° | T4 |
| | | High Resolu- tion | 1 in. | $f/8$ | 50° | S5 |
| | | High Resolu- tion | 2 in. | $f/8$ | 46° | T4 |
| Goerz | ... | Artar Apo Process | 4-70 in. | $f/9-16$ | 44° | T3 |
| | | Goetz Process | $8\frac{1}{2}$ -24 in. | $f/6.8-10$ | 54° | T3 |
| Kern | ... | Apo-Repro | 210-300 mm. | $f/6.6-9$ | 53° | T3 |
| Kodak | ... | Ektar | 2 in, 3 in. | $f/4.5$ | 50° | T7 |
| | | Ektar | 4 in. | $f/4.5$ | 50° | T3 |
| | | Ektanon | 10 in. | $f/8$ | 50° | T3 |
| | | Ektanon | 2-4 in. | $f/4.5$ | 50° | T1 |
| | | Ektanon | $5\frac{1}{2}$ -10 in. | $f/4.5$ | 50° | T4 |
| | | Process Ektar | 12-30 in. | $f/10$ | 36° | E1 |
| Rodenst. | ... | Ysaron | 210 mm. | $f/4.5$ | 52° | T4 |
| | | Apo-Ronar | 300-800 mm. | $f/9$ | $44^\circ-48^\circ$ | T3 |
| Ross | ... | Resolux Enlarging | 50-110 mm. | $f/3.5, 4$ | 50° | T4 |
| | | Process Lens | $9\frac{1}{2}$ -48 in. | $f/10-12.5$ | $34^\circ-37^\circ$ | S3 |
| | | Ensar | 105 mm. | $f/4.5$ | $2\frac{1}{2} \times 3\frac{1}{2}$ in | T4 |
| Steinhell | ... | Culminar | 50-210 mm. | $f/4, 4.5$ | 50° | T4 |
| | | Cassar | 50-105 mm. | $f/3.5, 4.5$ | 50° | T1 |

| <i>Maker</i> | <i>Name of Lens</i> | <i>Focus</i> | <i>Aperture</i> | <i>Field Covered</i> | <i>Diagram</i> (p. 183 also pp. 153, 173) |
|--------------|---------------------|--------------|-----------------|----------------------|-------------------------------------------------|
| T. T. & H. | ... Ental | 50-127 mm. | f3.5, 4.5 | 50° | T4 |
| | Copying Lens | 4 in. | f2-4 | 35 mm. cine | S5 and T7 |
| | Series VB | 9-36 in. | f8-16 | 35°-45° | T1 |
| | Series IX | 13-62 in. | f10-16 | 35°-45° | T3 |
| | Apotal | 9½-24 in. | f9 | 48° | T4 |
| | Microfilm | 20-50 mm. | f4 | 16 mm. cine | S5 |
| | Radiography | 8 in. | f1.4 | 5 x 5 in. | S5 |
| Voigtland. | ... Repro-Skopar | — | f3.5, 4.5 | — | T4 |
| | Repro-Ultrar | — | f2 | — | S13 |
| Wollensak | ... Raptar | 2-12 in. | f4.5 | 50° | T4 |
| Wray | ... Apo Process | 4-63 in. | f10-16 | 38° | T3 |
| | W. A. Lustrar | 12 in. | f10 | 50° | W2 |
| Zeiss | ... Apo Tessar | 140-900 mm. | f9 | 48° | T4 |

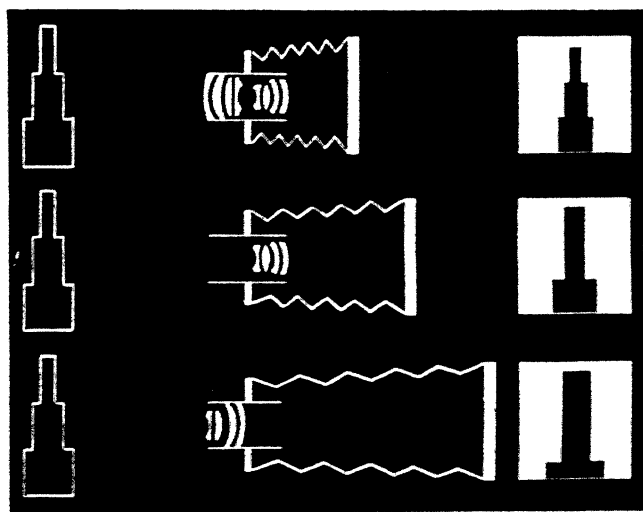
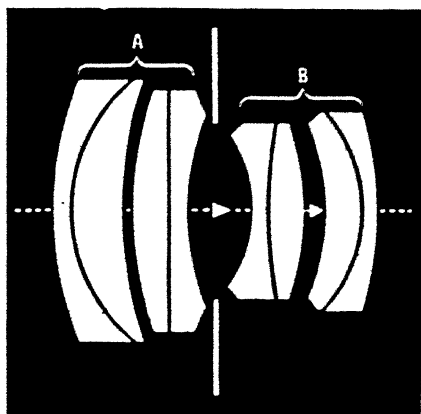
The general practice is to use a prism in front of the lens in process work, the effect of which is to bend the beam of light forming the image through a right angle. It cannot be emphasised too strongly in this connection that the quality of the prism is of paramount importance.

The main requirements for such a prism are that the glass blank from which it is cut shall be singularly free from faults such as strain and striae in the body of the material, that the angles shall be accurate to their nominal values within about one minute of arc, and that the surfaces shall be polished flat within half a wavelength of yellow light, i.e., within one hundred-thousandth of an inch. A very slight curvature, either spherical or cylindrical, of any of the surfaces—particularly the long reflecting surface—will introduce astigmatism (see p. 113). The production of prisms of a really high quality is a most skilled job.

One point of importance in connection with process prisms that is very easily overlooked (it is actually of importance in all optical instruments) is the fact that the blacking put on optical surfaces that are not used to transmit light, so that they will not reflect unwanted light either, must in fact absorb all light incident on it. One cannot take any arbitrary black paint or varnish and expect to find this total absorption of light, or anything approaching it. Suitable compounds are not usually publicly divulged by the firms using them. It follows from this that if by any chance the black is worn off the face of a prism (the triangular end face that is), or the edge of a lens, it is best returned to the maker for re-blackening. The use of a medium that is not perfectly suitable may result in the increased scattered light impairing contrast: this is of course of greatest importance under rigorous conditions of process work.

Convertible Lenses

To add flexibility to the use of miniature cameras the custom has grown up of building a camera, in fact, round a battery of lenses of different focal lengths and apertures. The frame covered remains the same size, and the different



Top : Taylor, Taylor & Hobson convertible lens. Each half may be used on its own, or the two of them used together, thus providing a choice of three focal lengths with the one set of components (p. 188).

Bottom : The units of a convertible lens give a progressively enlarged image of some particular object (p. 186).

A CONVERTIBLE LENS

focal lengths mean that the proportion of the picture occupied by an object increases as the focal length is increased.

The same thing could be done and was done with normal size cameras, and in fact still is done to a certain extent namely, to provide a battery of lenses with each camera. But whereas in the case of a miniature the lens is carried forward by building it up with extra metalwork on the mount, so that the lens clips into the bayonet holder or other attachment, with other types of camera the longer focus lens has to be taken further from the plate by extending the camera bellows, and it is only where a good extension is possible that a longer focus lens can be used.

With normal, as contrasted with miniature, cameras one method of providing three lenses in a battery is to build them into one lens, a "convertible" lens. This consists of two lenses, call them A and B, of fairly long focus, usually but not always different from one another. As a rule each of these lenses has to be used with the Iris diaphragm or stop in front of it. The corrections of the two lenses are adjusted so that the two lenses A and B can be screwed together and so provide a lens of shorter focal length than either of the separate components. Inevitably a certain amount of definition and correction of aberrations has to be sacrificed to produce a lens of this type, but with skilful design, the residual aberrations are small enough to be acceptable for all but the most critical work.

Page 187 shows the method and effects of using a typical convertible lens.

This type of lens is derived almost exclusively from the early Continental forms of symmetrical lenses and it supercedes the older type of so-called Casket lenses. These latter relied on the replacement of components in the *Triplet* or *Tessar* constructions and serious amounts of aberration were inevitable. In spite of the superiority of the true convertible over the older Casket forms, even the former fails to reach the high standard set by more conventional and less expensive forms of modern lenses. Most manufacturers now only produce these lenses to special order.

Supplementary Lenses

Another way of making a lens more flexible in its applications is to use it with supplementary lenses, either converging or diverging supplementary lenses.

The use of a converging lens for close-up work has been described on page 52, and no more need be said about that aspect of the matter. *The same type of lens can be used, moreover, for working conditions where a rather wider view is to be recorded on the plate than with the camera lens alone.* A converging supplementary lens in conjunction with the camera lens reduces the focal length of the latter, in effect, and since the plate covered is still the same size a greater angle of the scene is recorded. Suppose that the supplementary lens is to be used for portraiture at D inches from the front of the camera. Then as explained on pages 51-52, the focal length of this lens is D inches. If the camera lens has a focus of f inches, then the focal length of the lens formed by the two together is given within fairly close limits by the formula,

$$\text{Focal length of combination} = \frac{D \times f}{D + f} \text{ inches}$$

and the field recorded is $(D + f) \div D$ of that previously recorded. The image of any object produced when such a lens is used is smaller than when the camera lens is used alone in the ratio $D \div (D + f)$.

For instance if the supplementary is used for close-ups at 20 inches, then $D = 20$ inches, and with a 4 inch camera lens $f = 4$. The focal length of the combination is $(4 \times 20) \div 24$, i.e., $3\frac{1}{3}$ inches, and the field recorded is $1\frac{1}{2}$ of the old field (on a smaller scale, of course).

It is seldom profitable to use converging supplementaries to give more than $1\frac{1}{2}$ increase in the field recorded. They introduce among other things astigmatism and field curvature, and the definition is not to be compared with that given over the same area by a wide-angle lens. For rough work a spectacle lens can be used to get a visual idea of the effects produced. Since the focal length of the lens is given

above and spectacle lenses are usually described by their power in diopters, a table is given on page 365 showing the conversion of diopters to focal lengths.

A diverging lens can be used to lengthen the focus of the lens, and to record a smaller angular field on a larger scale, rather after the way in which this is done with a telephoto lens. The focal length of the combination, if the focal length of the diverging lens is N inches, and that of the camera lens is f inches, is given by,

$$\text{Focal length of combination} = \frac{N \times f}{N - f}$$

to a good approximation, and the increase in size of any image on the plate compared with the size obtained with the camera lens alone is in the ratio $N \div (N - f)$.

For instance, if the camera lens is 4 inches focus, i.e., $f = 4$, and the diverging lens is of 8 inches focus, i.e., $N = 8$, then

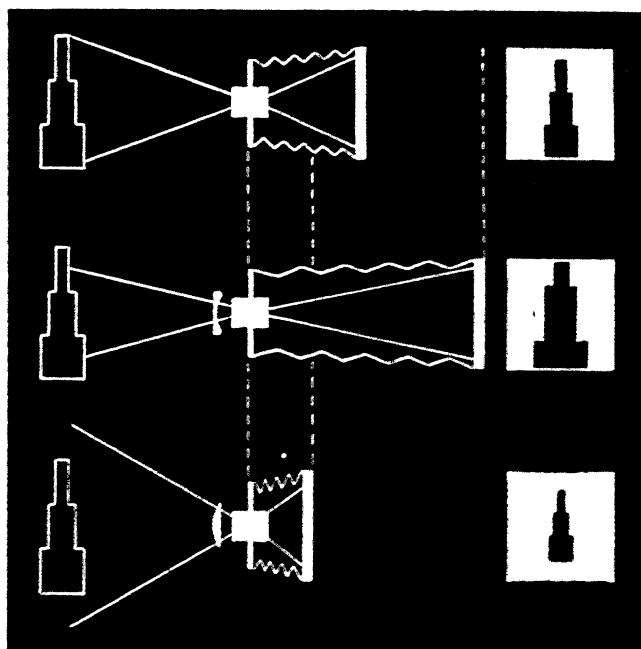
$$\text{Focal length of combination} = \frac{4 \times 8}{8 - 4} = 8 \text{ inches.}$$

and each image on the plate is $8 \div (8 - 4) = 8 \div 4$, i.e., twice the size it would have with the camera lens alone.

Both converging and diverging supplementary lenses can only be used when the camera focusing allows the lens to come close up to the plate, with the converging lens, and when a considerable extension is possible to accommodate the increase in effective focal length with the diverging lens. It is not usually profitable to use a diverging lens to more than double the focal length of the camera lens. What was said previously about spectacle lenses still holds.

Supplementary lenses as just described are rarely useful with lens apertures below f 4.5. This is about the fastest speed with which they give reasonable definition. And that brings up another point, namely the effective values of the aperture when a supplementary lens is used. The values engraved on the lens mount no longer represent the actual f /numbers. The rules are :

(1) With a converging supplementary lens the effective aperture is the f /number on the lens mount, divided by $(D + f) \div D$.



To obtain a larger Image of any part of a picture two procedures are possible ; the camera may be brought nearer to the scene, or the film or plate taken farther away from the lens. The extent to which the camera bellows will open out determines how closely the camera can be brought with the unaided camera lens alone.

Centre : By using a negative supplementary lens the plate or film can be taken further away from the lens without putting the Image out of focus. This means that from a given view-point a larger Image of an element of the scene is produced, but at the same time only a fraction of the original scene is taken than the camera lens alone would record. As a rule it is not profitable to use a negative lens in this way to give more than a two-fold enlargement (p. 190).

Bottom : When it is important to cover a fairly large angle a converging lens enables the plate or film to be brought nearer the lens and still keep the Image in focus. The Image of any element of the scene is then smaller. The ratio of increase in field that can be usefully produced is about $1\frac{1}{2} : 1$ (p. 189).

THE USE OF SUPPLEMENTARY LENSES

(2) With a diverging supplementary lens the effective aperture is the f /number on the lens multiplied by $N \div (N - f)$.

E.g., with the Iris in the lens at $f8$ and the actual cases quoted in detail above the effective apertures are : with the converging lens $f8 \div 1\frac{1}{2} = f6.7$, and with the diverging lens $f8 \times 2 = f16$. These are the apertures and f /numbers to be used in working out exposures and depth of field.

These formulæ hold for the cases where the supplementary lens, either converging or diverging, is used to change the focus of the camera lens and the combined lens is then focused on moderately distant objects. They also give the f /numbers that are to be used in depth of field calculations. When the combined lens is to be used for close-ups the corrections described on page 63 must be applied. The application of these corrections in the case where the object is at the focal point of the supplementary lens, as described on page 52, leads to the conclusion stated there that the f /number of the combined lens in these circumstances is in effect unchanged.

The use of supplementary lenses as envisaged above is rather different from their use as portrait attachments as described on p. 52, even though the object of using them may be the same in both cases to produce a larger image.

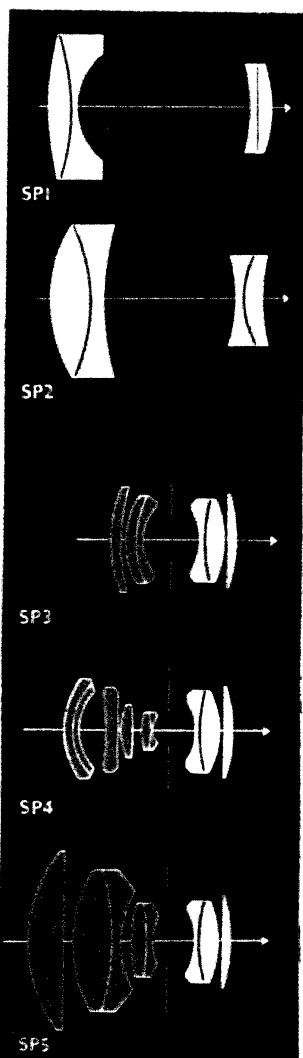
One way of obtaining a larger image is to bring the camera as near as possible to the scene, and then use a *converging* supplementary lens or portrait attachment to shorten the camera lens focus to allow it to focus the scene with a moderate bellows extension.

Another way is to keep the camera fixed but to increase the focal length of the lens by the use of a *diverging* lens. This normally needs an increased bellows extension.

When it is required to change the focal length of a lens without changing its distance from the sensitive material, an *afocal adaptor* may be used. This is, in fact, a Galilean telescope to be attached to the front of the camera lens. The camera lens is set at infinity, and focusing carried out by changing the separation between the groups of lenses in the adaptor. Such adaptors are of two kinds. The first working with the camera lens produces a larger image than given by the camera lens

SP1 and SP2 are supplementary lenses of the afocal adapter type, and do not change the required camera extension. They are specially popular with 8 mm. (and also 16 mm.) cine cameras fitted with a fixed lens. SP1 reduces the focal length of the camera lens with which it is used, and is thus a wide-angle attachment. SP2 increases the focal length and is thus a telephoto attachment.

SP3 to SP5 illustrate a convertible lens system utilising an interchangeable front component (shown shaded) and a fixed rear unit mounted behind the shutter. The three alternatives produce a standard lens SP3, a tele lens SP5, or a wide-angle lens SP4.



SPECIAL SUPPLEMENTARY LENSES

alone : thus it effectively increases the focal length of the latter. One example by Berthiot is shown in diagram SP2 on p. 193. Like all supplementary lenses of this type it comprises a front collective component spaced from a rear dispersive component. In order to be afocal and thus have no effect on camera lens extension, the separation between components must be equivalent to the difference between the positive values of their focal lengths. The magnification given by such a system is the focal length of the front component divided by that of the second. In this type of supplementary lens, which is suitable for use with wide aperture camera lenses, the optical aberrations have to be highly corrected and this can be achieved if the two components are made sufficiently complex.

The second kind working with the camera lens produces a smaller image but covers a larger angular field than the unaided camera lens; it effectively reduces the focal length of the latter. One example, also by Berthiot, is shown in diagram SP1 on p. 193. In this type the disposition of collective and dispersive powers is reversed back to front, but the above remarks concerning focal lengths and magnification still apply.

The use of these forms of afocal supplementary lenses is largely restricted to cinematography and miniature cameras where their relatively large bulk is not a serious handicap. Magnification factors of 2 and $\frac{1}{2}$ are quite usual.

More recently a different system has been developed in which that part of a lens which is positioned in front of the iris diaphragm can be replaced by another lens system to provide an alternative focal length. The rear lens components behind the iris are common to all the focal lengths provided, and their distance from the focal plane remains constant. Focusing for different object distances is provided by movement of lens elements in each interchangeable front unit.

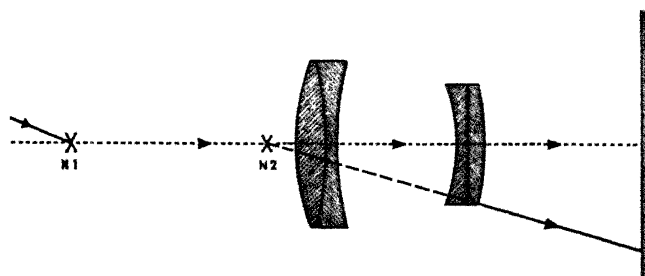
This arrangement is particularly useful in cameras incorporating a between-lens shutter of the *Compur* type, since it avoids interference with the shutter on changing lenses. The overall complexity of the lens construction can be less than a combination which includes the telescopic type of supplementary described above, but the front sections can only be used with the particular rear component for which they were designed.

Diagrams SP3, SP4, and SP5 on p. 193 show front interchangeable components of this type as made by *Rodenstock*. The basic lens SP3 is a 50 mm. *f*2 *Heligon C* covering a 24 × 36 mm. negative. This lens belongs to the *Speed Panchro* type as shown in diagram S5 on p. 161. The front half of the 50 mm. lens is replaced as in SP5 to provide an 80 mm. *f*4 lens and as in SP4 to provide a 35 mm. *f*5.6 lens.

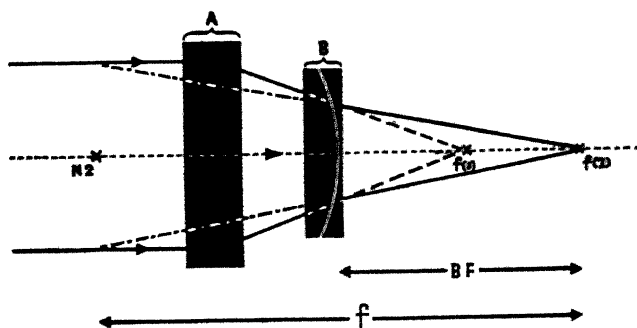
Very similar constructions yielding the same focal lengths are made by *Schneider*.

Telephoto Lenses

The introduction of the telephoto lens, as far as this country was concerned, was due to *Dallmeyer* in the 'nineties of last century. The main idea at that time was to provide



Both nodal points of a telephoto lens are in front of the lens (p. 36) The optical system, as far as subject-lens-image distance calculations are concerned, is therefore in effect not within the lens at all, but in an imaginary position in mid-air.



Parallel rays of light are rendered convergent by the lenses in A, and are then made less convergent by the diverging lens group B. Hence the back focus B.F. is much shorter than the equivalent focus f (p. 196). This is useful in practice, since the lens extension can be comparatively small in relation to the magnifying power of the system. The nominal magnification of the telephoto lens is in this instance not related to the image scale obtained with a normal focus lens. It is instead the ratio of the equivalent focus f to the back focus B.F. (p. 196). A $2\times$ telephoto lens may thus still produce an image 4 or 5 times as large as the normal focus lens for a particular negative size.

HOW TELEPHOTO LENSES WORK

a lens of long focus, which would give a larger reproduction on the plate, of a distant object, and at the same time have a short back focus, or distance from back glass to the plate, so that it would conveniently fit a normal camera.

This aim in making or using a telephoto lens still holds at the present time. But with the advent of miniature and small hand cameras, as well as movie cameras, that may be fitted with telephoto lenses, there is another advantage, namely that a long focus lens is used which has a short over-all length from the film to the front of the lens.

This makes for easy handling and rigid mounting, and is important with present-day standards of definition.

The principle is shown on p. 195. It comprises a lens or set of lenses that form a converging lens.

Rays of light through this forward lens, marked A on p. 195 that are initially parallel to the axis are made to converge towards the focus marked $f(1)$. Before they reach this focus they are intercepted by the negative or diverging lens, marked B, which reduces the convergence of the rays so that they now aim at the focus marked $f(2)$.

$f(2)$ is the rear-focal point of the lens, as explained on page 24. The distance of $f(2)$ from the last glass surface in the lens is the back focal length, which is the important feature to be taken into account when mounting the lens in a camera. If the rays aiming at $f(2)$ are continued backwards to meet the initial rays parallel to the axis, the points where the two sets cut lie on the rear principal plane, also defined on pages 26-27. Where this principal plane cuts the lens axis is the rear nodal point, and the distance from the rear nodal point to the rear focal point is, of course, the equivalent focal length of the lens. *The important feature to notice is that the rear nodal point is out in front of the lens, and that the back focal length is very much shorter than the equivalent focal length.*

The ratio of the equivalent focal length to the back focal length can be defined as the "power" of the telephoto lens. For instance with a typical telephoto of 10 inches focus, and 5 inches back focus, the power of the lens is 2, or 2 diameters, or 2X. The effect of using a telephoto

of 2X power is approximately to produce an image twice the size given by a normal lens with the same back focus.

In the early days of the telephoto lens high magnifications were demanded, powers of the order of 10X were asked for, and another practice was to make allowance for separating the converging and diverging lenses so that the power could be changed. Inevitably these meant that the definition was not up to anything like modern standards.

The majority of telephoto lenses manufactured to-day are of fixed power and the magnification is restricted to 2X or at the most 3X, the only exception being some very large lenses for news-reel work of about 56 inches focal length.

Under these conditions it is possible to produce lenses having really high standards of definition.

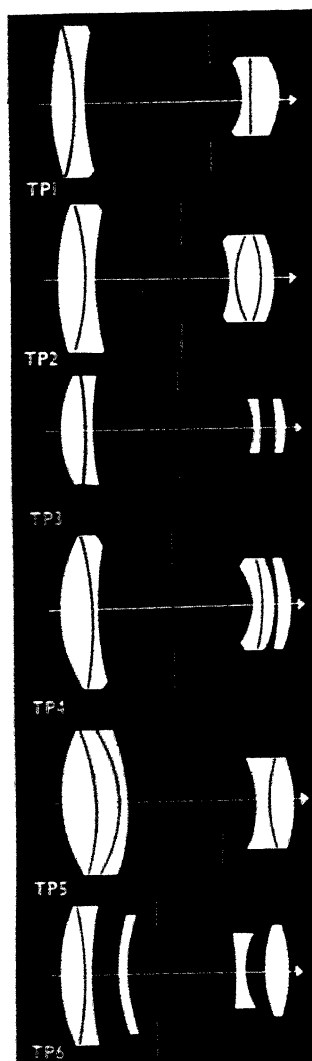
The main difficulties to be overcome in designing telephoto lenses are zonal aberrations and distortion. As a general rule, if the complexity of construction remains constant, the angular field that a telephoto lens can cover will decrease as the relative aperture is increased. When wide aperture and wide field is required simultaneously the complexity of construction becomes considerable.

Diagram TP8 on p. 199 is one example of the degree of complexity required.

The correction of aberrations to provide wide aperture alone also requires increased complexity. Diagram TP9 on p. 199 shows a *Taylor, Taylor & Hobson* telephoto lens with an aperture of $f2.3$. This lens is made for cinematography, and is one of the few photographic lenses which has a strongly curved concave surface at the rear.

Distorted Perspective : There is next to be considered a type of distortion often met with when a telephoto is used, namely the violent foreshortening of a scene, as in news-reel motion picture shots of sporting events.

The essential feature that is responsible for the distortion is the fact that the distance of the taking camera from the scene is comparatively great, while the picture produced by its sheer size suggests a close viewing point. The long focus of the telephoto lens together with the short focus of the projection lens result in the actual gross size of the

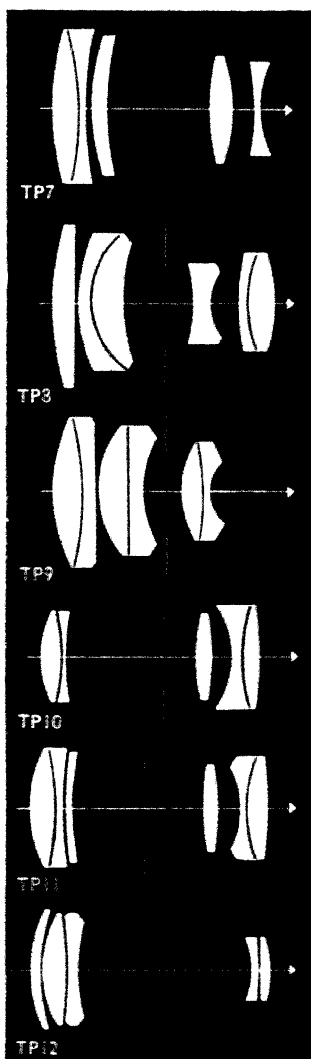


The telephoto lenses on this page differ mainly in the construction of their dispersive components. The top diagram TP1 illustrates one of the first telephoto lenses to be designed as one unit. Prior to the introduction of this form of lens, a telephoto effect was usually obtained by means of a dispersive component placed at a distance behind a conventional camera lens. The use of a camera lens with corrected aberration at the front is more of a hindrance than a help in achieving a good performance.

TP2 is a construction adopted in the Ross Teleros and Wray Plustrar.

TELEPHOTO LENSES

These telephoto lenses illustrate variations of front collective component as well as the rear component. TP9 is of interest since it is one of the very few photographic lenses having an exterior concave surface. The relative aperture of this latter form is about $f/2.3$, which is unusually wide for telephoto lenses.



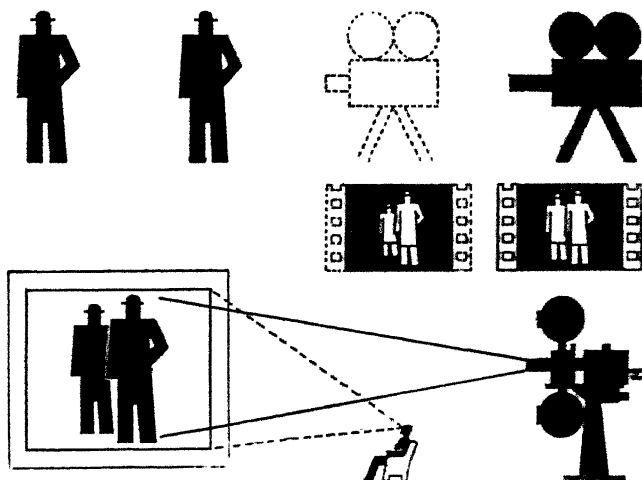
TELEPHOTO LENSES

reproduction on the screen, but they do not change the *relative proportions of parts* of the scene.

These latter, as they are seen on the screen, are just those recorded by the taking lens from its distant viewpoint. Now, when two subjects of the same size are photographed from a distant point, they produce images of practically the same size. This is in contrast to the case where a close viewpoint is used : then the extra distance of one subject makes an appreciable difference to the size of its image. This has already been shown on p. 38. The pattern of black and white thrown on the screen suggests, however, a fairly close taking position, owing to the very size of the objects depicted. This may receive further psychological emphasis with a comparatively close viewing distance in the cinema. In other words the image on the screen, because of the contradiction of its size and its proportions, appears strongly foreshortened. The feeling of discomfort arising from this is heightened by the fact that, again owing to the distant viewpoint of the telephoto lens, a "flatter" pattern is presented than we usually get in close distance viewing ; considering the size of the subject, we do not see enough of the "sides" and they seem to be lacking in "plastic" qualities.

Depth of Field : The final thing to discuss is the depth of field of a telephoto lens.

In many ways these lenses can be considered as being merely long focus lenses and the depth of field worked out as explained on pages 59-73. But there is another way of looking at the matter that is equally justifiable. Suppose, to take a concrete case that a 5 inch lens of normal construction is used to cover a plate or film just under $4\frac{1}{2}$ inches by $3\frac{1}{4}$ inches. As explained on pages 59-73 to see this at the right perspective the negative has to be enlarged in the ratio $10 \div 5$, i.e., twofold, in order that it may be examined at the least distance of clear vision, namely 10 inches. Now replace the 5 inch lens by a telephoto lens having the same back focus, namely 5 inches near enough, and 10 inches focal length covering the same plate. The image on the plate is



The foreshortening sometimes seen in newsreel shots when a telephoto lens has been used is due solely to the great disparity between taking and viewing conditions. When the camera is at a distance from the scene the images of two objects behind each other may appear to be nearly of the same size, as shown in the *upper right* diagram. The dotted line diagram shows the more contrasted image proportions peculiar to a nearer taking position. Thus the telephoto image projected on the screen has the proportions of the image taken from a distance but, because of the size of the subjects, it appears to have been taken from a close position. This accounts for our feeling of discomfort, particularly when viewing the scene from the front stalls. The perspective presented to us belies our own physical experience in viewing such scenes in nature.

FORESHORTENING WITH A TELEPHOTO LENS

seen at the correct perspective when viewed from 10 inches without any enlargement being necessary. But it is a perfectly natural thing to give the plates taken with the two lenses the same degree of enlargement, and look at them at the same distance, so as to get the advantage of the long focus and large images of the telephoto.

This twofold enlargement of the telephoto negative was not contemplated when the method of working out depth of field charts was explained on pages 59-73. What was envisaged there was a degree of enlargement to give the correct perspective with the picture viewed from a distance of 10 inches, and not any enlargement over and above that needed for this purpose, such as encountered here. Because of the twofold enlargement given in the case just dealt with, above what was intended on pages 59-73, the disc on the plate must be only half the size previously allowed. *The effect of this is to double the hyperfocal distance as previously calculated. After that everything proceeds normally with the newly-found hyperfocal distance in place of the old.*

With the same lines of reasoning the hyperfocal distance of a 3X telephoto is multiplied by 3.

What it is important to understand is the exact implication of the line of argument given. It is only a special example of what happens when a degree of enlargement is given to a negative in excess of that required in the orthodox calculations on pages 59-73.

The enlargement demanded on pages 59-73 was required to get the perspective right at a distance of 10 inches. Suppose that a 4 inch focus lens is being used. Then the enlargement needed, as explained there, is $10 \div 4$, i.e., $2\frac{1}{2}$ diameters. The circle of confusion at 10 inches is to be .01 inch. (If it is smaller, .005 inch say, then all that happens is that in every case the hyperfocal distance is double that of the standard based on .01 inch. A disc of .005 inch is rather too small a size to be taken for routine depth of focus estimates, the orthodox diameter of .01 inch is better.) The disc on the original negative must therefore be .004 inch diameter, and this is used automatic-

ally in the depth of field calculations already described.

Suppose that, however, a 4 times enlargement is given to the negative when printing. To get the correct perspective the enlargement should be viewed from a distance of 4 inches by 4 inches, i.e., 16 inches. The above depth of field calculations would serve all right if this viewing distance were held to. It should be in theory, but it seldom is in practice. The odds are that in ninety-nine cases out of a hundred the enlarged picture just quoted would be examined finally from a distance of 10 inches. It happens at every photographic exhibition, except with hardened initiates, that everyone gradually edges up to any particular print to see what it looks like from close quarters. There is a certain amount of foreshortening introduced but usually it is quite inappreciable and in no way disturbing.

With the 4x enlargement viewed at 10 inches the disc on the negative must be only .0025 inch diameter, compared with the standard .004 inch diameter. As a result the hyperfocal distance is $4 \div 2\frac{1}{2}$, i.e., 1.6 of what it is in the standard case.

This is a perfectly general result. *If the enlargement demanded on page 58 is M, and enlargement actually given is A, and the picture is examined, as is really only natural, at a distance of 10 inches then the previous hyperfocal distance, calculated as explained on page 66, call it H(1), has to be multiplied by $A \div M$, to give the new hyperfocal distance that should really be used.* In the example just quoted $M = 2\frac{1}{2}$, and $A = 4$ so that the orthodox hyperfocal distance should be multiplied by $4 \div 2\frac{1}{2}$, i.e., 1.6 as mentioned above. If the positive is to be examined at 10 inches with a smaller enlargement than that required in the usual calculation, say as a contact print taken with a 4 inch lens, then the hyperfocal distance is decreased, using exactly the same rule as given immediately above.

What this discussion implies relative to telephoto lenses, and the rather rough and ready rule of multiplying the hyperfocal distance by the power of the telephoto, is that photographs taken with a telephoto are very apt

to be examined at close quarters and that as a rule this should be allowed for in working out the hyperfocal distance.

It is impossible to dogmatise about depth of field except in the most elementary cases. Photography is both an art and a science. It is fairly easy to say exactly what will happen from the scientific point of view, to give definite rules for developing to a required gamma, and so on. But it is considered to be impossible to legislate for the artistic side of photography. The best results are produced by the exercise of taste and intelligence, and all that can be done is to give the general lines that must be followed. This holds for depth of field among other things.

What has been said above is admittedly a refinement of the idea of the depth of field of a lens, but it should not be neglected by the advanced worker who is prepared to use it as a starting point for his own work. Where a simple and straightforward working out of depth of field is required it is best to use the methods given on pages 59-67, which are the orthodox methods, and to apply these unchanged to telephoto lenses.

What has been said in criticism of the depth of field, as worked out by the first method on pages 59-67 applies equally well to the second method where attention is concentrated on a disc of confusion of a specified diameter. The real difficulty is to decide exactly what should be the diameter of the disc. It should not be so large as to give too blunt and diffuse definition at the limits of the depth of field, nor so small as to give too sharp a definition there. Some compromise has to be reached. It is usual to take a diameter of .002 inch for miniature work where this type of calculation is mainly used. For cine work with short focus lenses the diameter can be reduced to .001 inch. Below this the grain of the film, especially if a fast panchromatic film is used, becomes comparable with the size of the disc of confusion. Except in very special cases there is no point in taking the diameter of the disc below .001 inch.

Enough has been said above and on pages 59-73 to enable the photographer to construct his own depth of field charts and to know exactly what they imply. It is not profitable to rely too much on formulæ even though they are well established. The usual thing for the mathematician working them out is to make assumptions, and then give the formulæ as correct only providing that the assumptions are correct. Too often this last proviso is lost to sight in the course of years. It pays to understand the implications of the formulæ and then modify them as individual taste and intelligence dictates.

All this is apart from experimental methods of dealing with depth of field, described in the next chapter, and needed because of the criticism raised both here and on page 129.

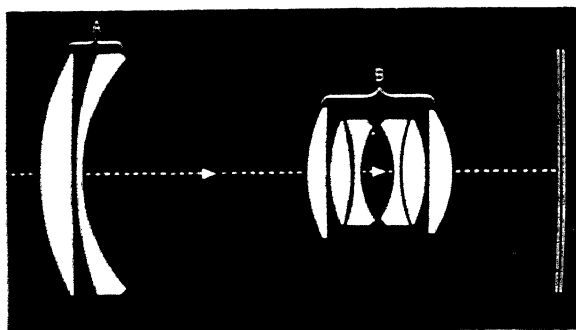
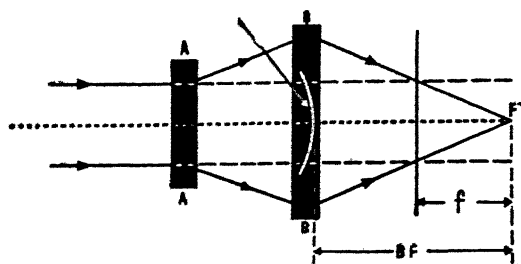
XXVIII.—TELEPHOTO LENSES

| <i>Maker</i> | | <i>Name of Lens</i> | <i>Focus</i> | <i>Aperture</i> | <i>Field Covered</i> | <i>Diagram</i> (pp. 198-199) |
|----------------------|-----|---------------------|----------------|-----------------|------------------------|---------------------------------|
| <i>Agilux</i> | ... | Telephoto | 160-300 mm. | f5.5 | 2½ × 2½ in. | TP1 |
| <i>Aidis</i> | ... | Projection | 10-12 in. | f3.5, 4.2 | 8°-10° | TP7 |
| <i>Berthiot</i> | ... | Tele Objectif | 145 mm. | f4.5 | 16° | TP5 |
| | | Tele Cinor | — | f2.5 | 31° | TP8 |
| <i>Dallmeyer</i> | ... | Dallon | 4-60 in. | f5.6-8 | 30° | TP1 |
| | | Adon | 6-24 in. | f4.5 | 26° | TP1 |
| | | Cine Tele. | 1½-12 in. | f3.5-5.6 | 16 mm. cine | TP1 |
| <i>Kilfitt</i> | ... | Tele-Kilar | 300 mm. | f5.6 | 24 × 36 mm. | TP1 |
| <i>Leitz</i> | ... | Telyt | 200 mm. | f4.5 | 24 × 36 mm. | TP6 |
| <i>Meyer</i> | ... | Telemegor | 150-400 mm. | f5.5 | 12°-19° | TP1 |
| <i>Ross</i> | ... | Teleros | 6½-22 in. | f5.5 | 30° | TP2 |
| | | Teleros | 9-25 in. | f6.3 | 19° | TP2 |
| | | Teleros | 40 in., 50 in. | f8 | 15° | TP3 |
| <i>Schneider</i> | ... | Tele Xenar | 75-240 mm. | f3.8, 4.5 | 34° | TP4 |
| | | Tele Xenar | 150-360 mm. | f5.5 | 34° | TP1 |
| <i>T.T. & H.</i> | ... | Series VIII | 8½-36 in. | f5.6-6.3 | 30° | TP1 |
| | | Telekinic | 3-6 in. | f3.5-4.5 | 16 mm. cine | TP1 |
| | | Panchrotal | 2.8-4 in. | f2.3 | 8 and 16 mm. cine | TP9 |
| | | Tele-Panchro | 8-22 in. | f4 | 35 mm. & 24 × 36 mm | TP12 |
| <i>Voigtland.</i> | | Telomar | 100-360 mm. | f5.5 | 33° | TP10 |
| | | Dynaron | 100 mm. | f4.5 | 24 × 36 mm. | TP11 |
| <i>Wollensak</i> | ... | Cine Raptar | 3-6 in | f4.5 | 16 mm. cine | TP1 |
| <i>Wray</i> | ... | Plustrar | 6-18 in. | f4.5-6.3 | 27° | TP2 |

In many instances lenses for 8 and 16 mm. movie cameras which are called telephoto lenses are not actually of true telephoto form, but simply long focal length lenses of more conventional types. These are listed in their appropriate table.

Inverted Telephoto Lens

A lens closely allied to the telephoto lens is the inverted telephoto construction used when a short focal length is

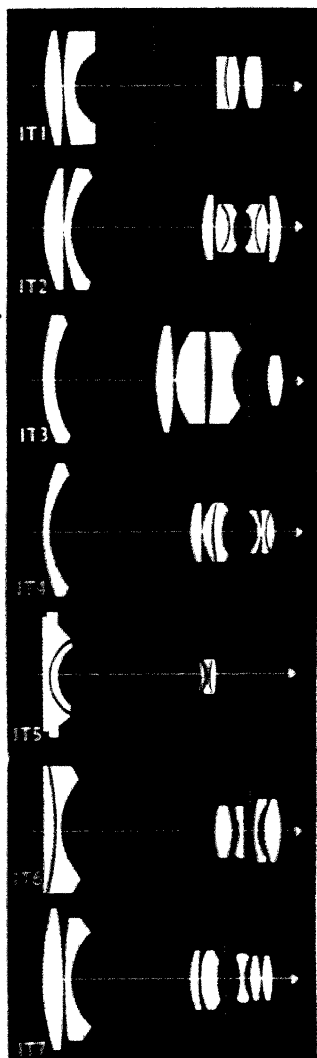


Top : The principle of the inverted telephoto lens. Parallel rays are rendered divergent by the lens group A, and then made convergent by the lens group B. Hence the equivalent focal length f is much shorter than the back focus B.F. (p. 210).

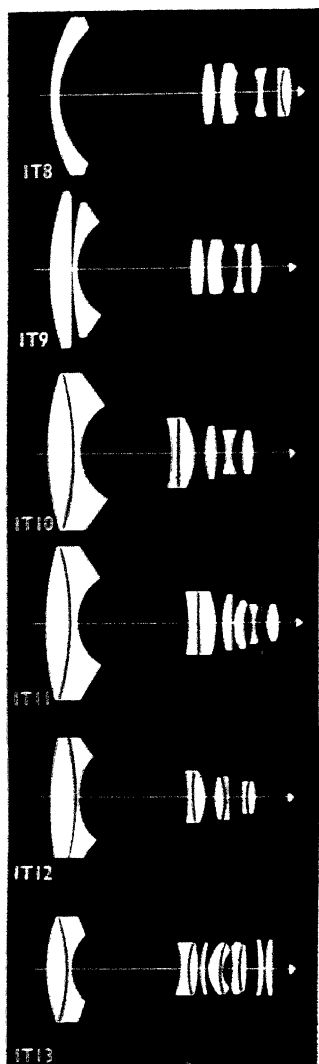
Bottom : An Inverted telephoto lens made by Taylor, Taylor & Hobson. The group A constitutes a diverging lens system. B is a converging lens of Speed-Panchro type. The resultant effect of these two is to provide a converging lens with long back focus. Such a lens is necessary when there is an extensive prism system between the lens and the film. The type shown is especially suitable for 35 mm. film work. For the smaller lenses used on 16 mm. cameras a rather simpler construction can be used (p. 210). This type of lens has been used for the Technicolor camera.

AN INVERTED TELEPHOTO LENS

Inverted telephoto lenses comprise a front dispersive member and a rear collective member. It is a fairly recent innovation and it is likely to become increasingly important in the future. The main advantages of this form is its capability of covering a wide field at wide apertures and greatly reduced vignetting. It also has a relatively large clearance between the rear surface and the focal plane. This clearance assists the fitting of very short focal length lenses to some cameras which are unable to accommodate conventional short focus lenses. This type of lens is very large, relative to its focal length, and is rarely made in focal lengths greater than 2 inches.



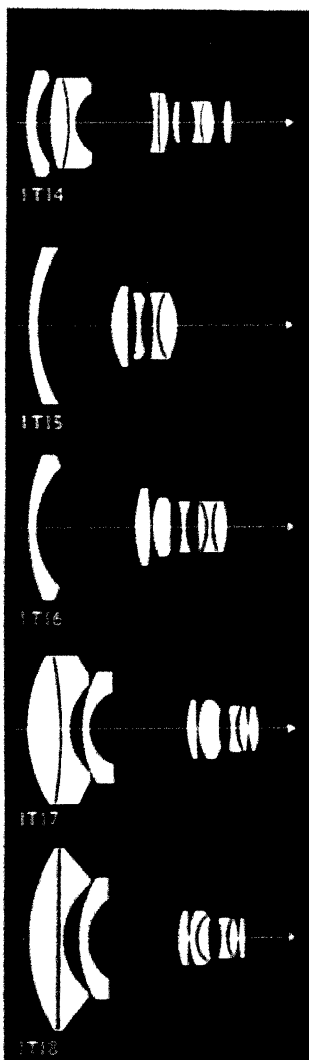
INVERTED TELEPHOTO TYPES



These are more examples of inverted telephoto lenses. IT8 and IT9 are exemplified by the *Angenieux Retrofocus*: the diagrams IT10, IT11, IT12 and IT13 show constructions which may be considered as wide angle supplementary attachments in front of conventional camera lenses. For example the *Schneider Cinegon* lens shown in IT11 is, in general terms, the supplementary lens of diagram SP1 (p. 193) in front of the triplet form of diagram T5 (p. 161). Examples of IT10, IT12 and IT13 are the *Wollensak Cine-Raptar* series.

INVERTED TELEPHOTO TYPES

Some of the more recent designs incorporate two dispersive front components. Examples are the *Berthiot Cinor*, IT14, the *T.T. & H. Toytal* as shown in IT17, and the *Double Speed Panthro* of IT18. Most of these are generally used for cine work, both substandard and 35 mm.



INVERTED TELEPHOTO TYPES

required and at the same time a long back focus is needed. (This is the exact opposite of what is needed when a telephoto lens is used.) Typical cases are in colour cinematography as worked by the *Technicolor* process, where the prism system has to be accommodated between the lens and the film, and in fitting short focus lenses of about 12½ mm. focus to turrets on 8 and 16 mm. film cameras.

The principle of the inverted telephoto is shown on p. 206. Rays of light initially parallel to the lens axis are made to diverge by the diverging set of lenses marked A. The rays then hit the converging lenses marked B, and come to a focus at F. The back focus is the distance of F from the rear-most glass surface in the lens. The equivalent focus is the distance of F from the plane where the continuations of the initial parallel rays meet the rays converging to F, as shown on p. 206. The back focus is greater than equivalent focus.

More recently it has been realised that this form of lens has some very desirable characteristics compared with those of conventional wide-angle lenses. In addition to the long back focus already described it can be designed with improved vignetting factors and it presents a different, and in some ways easier, mounting problem.

Its use is largely restricted to cinematographic and miniature cameras since it is a very bulky form of lens relative to its focal length. Distances between front surface and focal plane of up to 5 times the focal length are quite common and diameters are correspondingly large, especially the front dispersive component.

In some ways this form can be considered as a wide-angle supplementary lens (see p. 194) permanently positioned in front of a conventional form of lens having the long focal length necessary for the specified back focus. Diagrams IT8, IT9, IT10 and IT11 on p. 208 have been designed in this way. Under certain conditions this line of attack results in an unnecessarily complex system and the modern trend is to design inverted telephoto lenses without reference to more conventional forms.

XXIX.—INVERTED TELEPHOTO LENSES

| <i>Maker</i> | | <i>Name of Lens</i> | <i>Focus</i> | <i>Aperture</i> | <i>Field Covered</i> | <i>Diagram</i> (pp. 207-9) |
|----------------------|-----|----------------------|------------------------------------|-----------------|----------------------|-------------------------------|
| <i>Angenieux</i> | ... | Retrofocus R 21 | 10 mm. | f1.8 | 16 mm. cine | IT9 |
| | | Retrofocus | 18.5, 24 mm. | f2.2 | 35 mm. cine | IT16 |
| | | Retrofocus | 35 mm. | f2.5 | 24 x 36 mm. | IT8 |
| | | Retrofocus | 28 mm. | f3.5 | 24 x 36 mm. | IT9 |
| <i>Berthiot</i> | ... | Cinor | 6 mm. | f1.9 | 8 mm. cine | IT14 |
| | | Cinor | 10 mm. | f1.9 | 9.5 & 16 mm. cine | IT14 |
| <i>Dallmeyer</i> | ... | Inverted Tele. | $\frac{1}{2}$ -1 $\frac{1}{2}$ in. | f2.5-3.5 | 52° | IT1 |
| <i>Schneider</i> | ... | Cinegon | 6.5 mm. | f1.9 | 8 mm. cine | IT11 |
| | | Cinegon | 11.5 mm. | f1.9 | 16 mm. cine | IT11 |
| | | Cinegon | 20 mm. | f2 | 35 mm. cine | IT11 |
| <i>T.T. & H.</i> | ... | Taytal | 6.5 mm. | f1.75 | 8 mm. cine | IT17 |
| | | Ivocal | 12.5 mm. | f1.4 | 8 mm. cine | IT3 |
| | | — | 12.5, 15 mm. | f1.8 | 16 mm. cine | IT18 |
| | | Speed Panchro | 18.25 mm. | f1.7 1.8 | 35 mm. cine | IT18 |
| | | — | 35, 40 mm. | f2 | 35 mm. cine | IT2 |
| | | Double Speed Panchro | 28 mm. | f2 | 24 x 36 mm. | IT18 |
| <i>Voigtland.</i> | ... | Ultron | — | f5.8 | — | IT5 |
| | | Skoparon | 35 mm. | f3.5 | 24 x 36 mm. | IT15 |
| <i>Wollensak</i> | ... | Cine Raptar | 6.5, 9 mm. | f2.5 | 8 mm. cine | IT10 |
| | | Cine Raptar | 6.5 mm. | f1.9 | 8 mm. cine | IT12 |
| | | Cine Raptar | 12.5 mm. | f1.5 | 16 mm. cine | IT13 |
| <i>Zeiss</i> | ... | Flektogon | 35 mm. | f2.8 | 24 x 36 mm. | IT4 |

Variable Focus Lens

And lastly, an example of what the modern optical industry can do is the variable focus lens shown on p. 213 and used for "zoom" shots in the film studios.

In such a shot the aim is to produce the effect of bringing the camera nearer the scene without actually moving it. This can be effected by gradually increasing the focal length of the lens so that it produces a progressively larger image.

With a variable focus lens three things have to be main-

tained as the focus is changed. These are : the correction of the aberrations, the exact focusing of the image on the film, and an unchanged f /number even though the focal length is changed. All these have to be brought about automatically by turning a crank.

Skilful design and superb workmanship are needed to get good results with this type of lens.

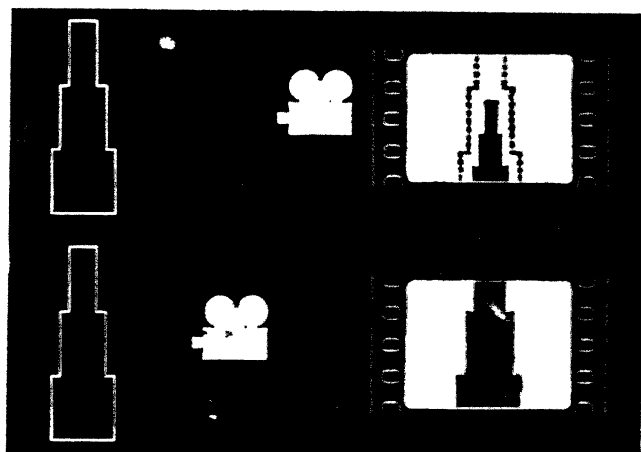
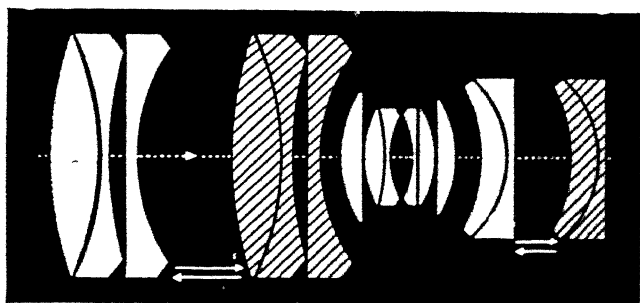
Variable focus lenses have also been used for projection purposes, mainly in commercial cinemas where they have permitted the projection from standard 35mm. film to be varied in size while the film is running.

A continuous variation of focal length over a useful range obviously removes the necessity of changing camera lenses during shooting of one scene and thus the possibility of losing an interesting event during the change-over. Although continuous film sequences can be obtained by skilful cutting and editing of the film, such procedures are not possible in the transmission of television pictures. The particular usefulness of variable focus lenses for television has stimulated the design of these lenses to a considerable extent and it is likely that some of these developments will eventually be used in a modified form for cinematography.

NOTE :—Throughout this chapter a number of the lenses available have been described, which have been listed in makers' catalogues. But one point should be made clear. In addition to the lenses described here, and to those given in the lists on pages 151, 159, 168, 176, 182, 185, 205, 211, it is often possible to get special lenses for individual jobs from the manufacturers : there are designs that have been developed and variants of catalogued designs that have not found their way into regular production, and for specialised work it is always worth while enquiring whether any of these are available and suitable.

Mirror Lenses

The image-forming systems so far described have been orthodox lenses in the sense that light has gone through the transparent media, namely glass, of which they have been made, suffering refractions at the various air-glass surfaces embodied in the lens. A defect that is practically inevitable in such a system is the existence of a secondary spectrum. In many cases it is not unduly objectionable, but there are occasions—especially where high aperture lenses are con-



A variable focus lens made by *Taylor, Taylor & Hobson*. The shaded elements are movable. While the focal length is changed the f number of the lens and the position of the image it forms remain unchanged.

Bottom : As the focal length of the lens is increased the size of the image of the object in the field of view increases. Normally this increase in image size is effected by moving the camera towards the object, and in viewing the result it is not easy to determine which method of procuring the enlargement has been used (p. 211). The change of perspective when the camera viewpoint is moved is usually detectable on direct comparison between the two methods.

A VARIABLE FOCUS LENS

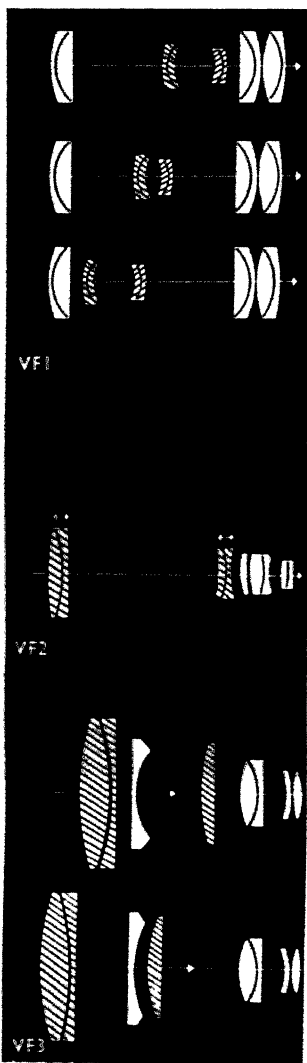
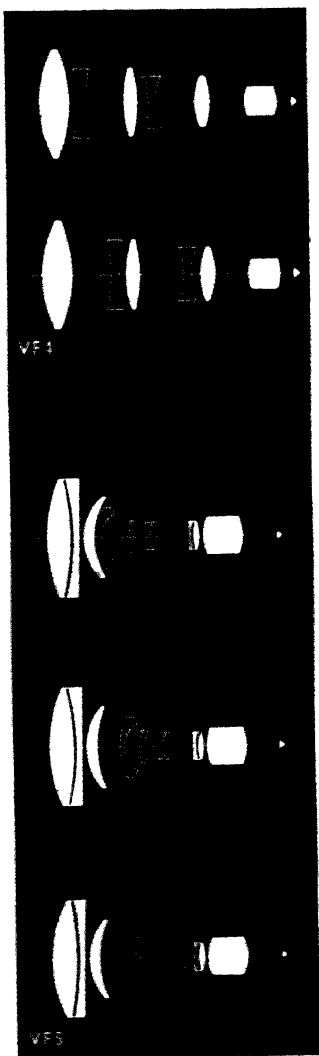


Diagram VF1 shows a *Watson* television camera lens with alternative ranges of focal length of 3 to 15 or 6 to 30 inches. Diagram VF2 shows a *Taylor, Taylor & Hobson* television camera lens with alternative ranges of focal length of 4 to 20 or 8 to 40 inches. These alternatives are provided simply by interchangeable rear components. In the 4 to 20-inch range the maximum aperture is $f4.5$ throughout, and in the 8 to 40-inch range $f8$. Diagram VF3 is a variable focus lens by *Berthiot* designed for 16 mm. cine cameras. The range of focal lengths is continuously variable between 20 and 60 mm. at an aperture of $f2.8$. The components which move to change focal length are shaded in all these diagrams.

VARIABLE FOCUS LENS TYPES

The *Berthiot Pan-Cinor 4* for 16 mm cine cameras shown in VF4 is an improvement of VF3. Both types require simple mechanical movements compared with other forms and there is a very slight shift of best focusing position in both as the focal length is varied. This shift is well within the depth of focus of the lens and its reduction by the more complex optical form of VF4 enables the zoom range to be increased to a factor of 4 at the wider relative aperture $f2.4$. The focal length is variable between 17.5 and 70 mm. and the lens incorporates a built-in reflex viewfinder.

Diagram VF5 shows a *Zeiss Ikon Pentovar* lens designed for 35 mm. cine cameras. The range of focal lengths is continuously variable between 30 and 120 mm. at, for variable focus lenses, the unusually wide relative aperture of $f2$. This lens is large relative to its focal lengths and the cine camera is positioned on a platform extending rearwards from the lens.



VARIABLE FOCUS LENS TYPES

cerned—when it is a matter of importance to reduce it to a minimum. For this, and for various other reasons, attempts have been made at different times to produce an image-forming system using reflection rather than refraction to bend the incident light rays.

An increased impetus has been given to the investigation of such systems in the last decade by *Schmidt's* discovery of the camera named after him. One form of the *Schmidt* camera is shown in the diagram on p. 217. It consists of a spherical mirror *M*, with a hole drilled in the centre, a plane mirror *P*, and a plate *S* carrying an aspheric surface. One form of the contour of the aspheric surface is shown on an exaggerated scale in the diagram on p. 217: the deviation from flatness is very small, of the order of a few thousandths or at the most hundredths of an inch. With such a simple system apertures up to more than $f/1.0$ have been realised with practically no secondary spectrum to speak of. Such *Schmidt* lenses have been proposed in more or less this form for the projection of television images formed on the screen of a cathode-ray tube.

The principal defect of the *Schmidt* lens as just described is the fact that its field is curved. To get the best definition the plate or film must be bent to take up the shape shown by the dotted line in the diagram on p. 217, or if it is used as a projection lens the cathode-ray screen must be curved in the same way.

Two main ways of flattening the field of a *Schmidt* lens have been described. One is to add a converging system of a simple type such as a plano-convex lens, as shown on p. 217, near the focal plane. This has little effect on the other aberrations, to a first approximation, but does flatten the field. The other is to use both a convex and a concave spherical mirror, as shown in the diagram on p. 217. The two mirrors have to be of the same radius of curvature. Systems of this second type, employing for the most part two plates bearing aspheric surfaces, are the subject of recent patents by *Warmisham*.

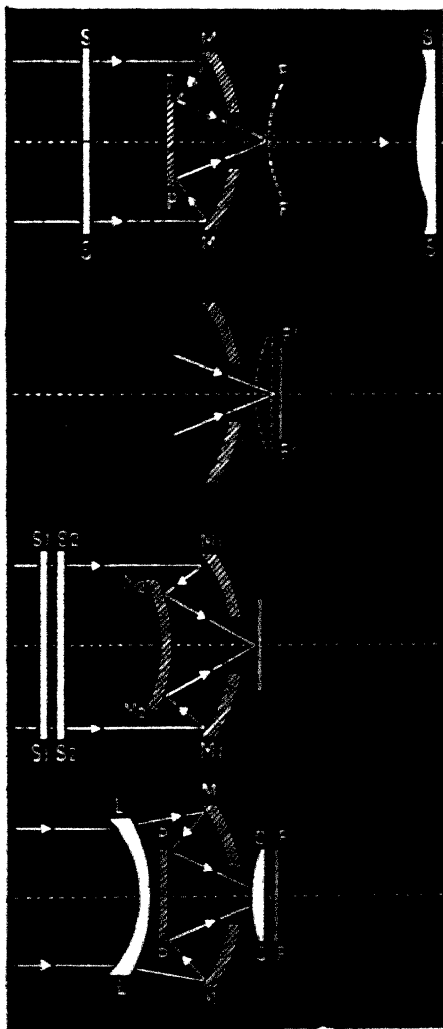
The defect, and it is an important one, of the systems just

Top left : A simple, though not the most primitive, form of Schmidt camera, comprising a concave spherical mirror, a plane mirror, and a correcting plate. Top right : The contour of one form of correcting plate shown on an exaggerated scale.

Second line : The field of this lens may be flattened with a plano-convex lens.

Lower : Alternatively a flat field is given by the system using two spherical mirrors M_1 , M_2 and two correcting plates S_1 and S_2 .

Bottom : A variant of this construction of particular interest, due to Gabor, employs only spherical surfaces. It comprises a weak meniscus lens L , a spherical mirror M , a plane mirror P , and a field-flattening lens C . The field FF is practically flat.



MIRROR LENSES

described is that at least one surface has a curve on it that is not of spherical form. The production of such surfaces on a commercial scale is a problem of outstanding difficulty. They have been made by astronomers, but there is a world of difference between making a few surfaces for observatories and manufacturing them on a mass-production scale. Aspheric correcting plates have been moulded from transparent plastic in the United States, but the production of the moulding dies is still a difficult problem.

For this reason special interest attaches to attempts that have been made to design a lens based on reflection rather than refraction which employs only spherical surfaces. One of these is shown in the bottom diagram on p. 217. Other forms have been proposed by the Russian *Maksutov*, by *Messrs. Wray*, by *Messrs. Taylor, Taylor & Hobson*, and others. Particularly noteworthy are the reflecting systems developed in Holland during the war by *Bouwers* of the *De Oude Delft Company*, using deep meniscus lenses to correct the aberrations introduced by a concave mirror. A 400 mm. $f5.6$ mirror lens made by that company is commercially available for use with 35 mm. cameras such as the *Leica*.

These mirror lenses seem an attractive proposition when one compares their simplicity with the complexity of standard refracting lenses, especially of high aperture, and takes into account that they are virtually free from chromatic effects, in particular that they have no secondary spectrum. In the longer focal lengths also, they represent a considerable saving in weight over standard types.

It should be realised that the beam of light incident on these mirror lenses is obstructed by that part of the system in front of the concave mirror. Special mechanical masking is necessary to prevent light passing through the various apertures and reaching the focal plane without suffering any reflection at all. These two factors are the main reasons why these forms have no adjustment of relative aperture. Usually they are designed and made for use under special conditions of magnification, aperture and field of view, and they are not always listed in manufacturers' publications.

The History of Lens Types

The historical line of development of the basic lens types has been in the following order : *single meniscus lens*, about 1812 ; *Petzval lens*, about 1840 ; *rapid rectilinear*, about 1866, developing into the *symmetrical type* in the Dagor and other lenses about 1890-1894 ; *Cooke Triplet type* about 1895 ; *primitive telephoto lens* about 1894, and *anastigmat telephoto lens* (designed by L. B. Booth) about 1914. The other minor types, variable focus and inverted telephoto lenses belong to comparatively recent times, while enlarging, process, convertible, wide-angle and soft-focus or portrait lenses are specialised variants of the basic types intended for particular uses.

Apart from the telephoto type, which is to some extent a separate branch away from the main line of development, the historical development corresponds very roughly to an improvement in performance. The symmetrical type as developed in the Dagor, Double Protar and other similar types employing two cemented groups of lenses, covered a larger field than the Petzval lens, although it was restricted to a much lower aperture.

The Cooke Triplet type, while not covering quite the same extent of field that was possible with the Dagor and allied types, covered a field distinctly larger than the Petzval type, was much more economical of glass and cheaper to produce than the cemented symmetrical type.

Taking everything into account, of all the basic lens types the Cooke Triplet by the late H. D. Taylor has been the most important from the point of view of the vast number of photographers.

In view of the common prejudice in favour of the great German houses it may be worth saying a few words on the subject. No expert will deny the excellence of their designs or the soundness of their constructions, or in any way under-rate them. Nor will anyone with an intimate knowledge of lenses under-rate the importance of the contributions

that English opticians have made. The achromatic lens was invented by *Messrs. Hall and Dolland* (both English), the rapid rectilinear lens was developed by *Steinheil* (German) and *Dallmeyer* (English) independently. The *Cooke Triplet* was a purely English development. The first anastigmat telephoto lens and the fore-runner of many designs of this type was designed by *L. B. Booth* (English) and the first $f/2$ lens covering a large field was designed by the Englishman *H. W. Lee* (*Speed-Panchro*).

The leading English and American makers have nothing to fear from, and are in no way inferior to the leading German manufacturers—except perhaps in advertising themselves.

The last war accelerated the growth of the optical industries of several countries, and France and the United States in particular are rapidly becoming less dependent on the import of German optical instruments.

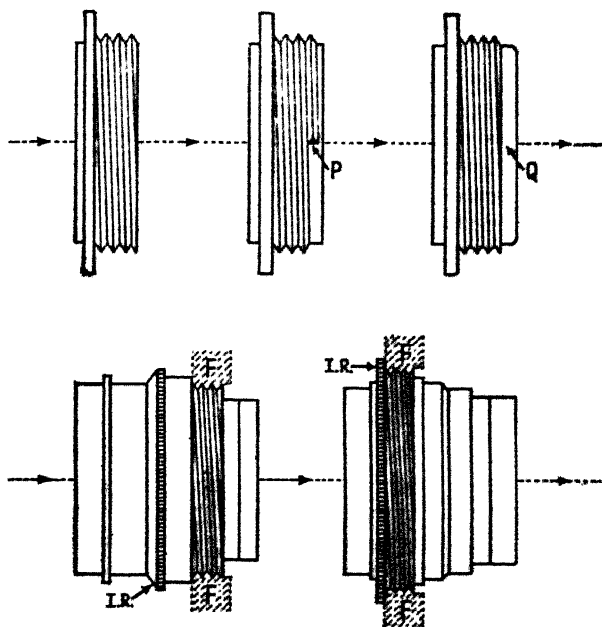
Lens Mounts

The main features of interest in lenses are the various arrangements of glasses in them and the way in which these have been chosen so that an adequate performance will result. Although on this reckoning the metalwork that goes round the glasses is of lesser interest the mounting of the lens as a whole is worth further consideration.

A point to be emphasised at the outset is the accuracy with which this metalwork is made. Tolerances of the order of a few ten-thousandths of an inch are not uncommon, and special methods of manufacture are adopted so that the bores in which the glasses fit are concentric within particularly close limits.

Regarding the styles of mounts there are three main types to be considered. These are : standard mounts, sunk mounts, and mounts incorporating a shutter.

The sunk and standard mounts differ only in the position of the flange screw by which the lens is attached to the camera. The two types are shown in the diagram on p. 221.



Top left : The standard threads on a mount have a sharp and tapered last thread.

Centre : The risk of crossing the threads is minimised by the use of an abruptly milled last thread *P*.

Top right : Alternatively a *pilot* may be used, as shown at *Q* (p. 223).

Bottom left : The thread by which a lens is attached to the front panel *FF* of a camera is at the back of a standard mount (p. 222).

Bottom right : In the case of a *sunk mount* the thread is at the front of the mount. *I.R.* is the Iris ring controlling the movement of the iris leaves (p. 222).

LENS MOUNTS

On the standard mount the flange screw is at the back, about a quarter of the length of the mount from the edge of this latter. With the sunk mount the flange is as far forward on the mount as it can be placed. This allows the whole of the lens barrel to be housed in the bellows of the camera. Sunk mounts are generally applicable to lenses to be fitted to hand cameras, barrel or standard mounts are more suited to stand and studio cameras.

As already mentioned the variation of the lens aperture is effected as a rule by the adjustment of an iris diaphragm. On lenses of the shortest focal lengths such an iris may consist of only two leaves, which move over one another so that they form a square aperture. In some other lenses the iris leaves are so designed that they form always an hexagonal opening for the light. The majority of iris diaphragms have a circular opening.

Usually the engraved apertures are rather bunched together at the narrow aperture end of the scale. This sometimes makes it difficult to set the narrower apertures of small cine and miniature camera lenses with any degree of precision. In recent times some attention has been given to the design of specially shaped iris leaves to provide an approximately linear iris scale.

The movement of the iris leaves is controlled usually by a moveable ring on the outside of the lens mount. This ring is readily accessible in the case of a standard mount, but with the sunk type of mount a slightly different form of fitting has to be adopted. One way of rotating the ring whose movement operates the leaves is through two pins attached to this ring. Another method is to rotate the whole of the front of the lens mount.

Lens mounts are generally made of brass, although in some cases aluminium is used. It will be found as a general rule that brass mounts are more serviceable than aluminium ones. Brass is not so brittle as aluminium, and is less subject to corrosion. This applies to the threads of the flange attaching the lens to the camera in particular. The threads of aluminium mounts are more prone to pitting by grease

and dirt which causes the jamming of the thread and makes it difficult to take the lens off the camera. Where, however, weight is of vital importance preference must be given to aluminium. The chromium plated cine, miniature, and projection lenses are usually made of brass that is chromium or nickel plated at a late stage of the lens assembly.

When a lens mount incorporates a shutter, i.e., when one has a between-lens shutter, the mounting of the lens elements, such as the glasses in their cells, in the shutter, must be carried out by the lens maker. Not even the best of present-day shutters are made with sufficient accuracy to permit of assembling the shutter and lens cells separately and then merely screwing them together.

There is a standard range of sizes of flange threads provided on British lenses and cameras, namely the standard R.P.S. threads listed as follows:

XXX.—STANDARDS OF FLANGE THREADS

| | | | | | | | |
|------------------|-------|-------|-------|-------|-------|-------|-------|
| Screw Diameter | 1.000 | 1.250 | 1.500 | 2.000 | 2.250 | 2.500 | 2.750 |
| Threads per inch | 24 | 24 | 24 | 24 | 24 | 24 | 24 |
| Screw Diameter | 3.000 | 3.500 | 4.000 | 4.500 | 5.000 | 6.000 | |
| Threads per inch | 24 | 12 | 12 | 12 | 12 | 12 | |

Continental mounts have metric threads as a rule.

Two minor points may be noted. The first is that a standard series of adapters is available carrying standard R.P.S. threads so that a lens may be screwed into the adapter and the two then screwed into the flange on the camera. In this way a lens may be fitted to a camera although the threads of the two do not match. Adapters of this type are made with special accuracy to keep the lens square to the plate or film. The second point is the ease with which a lens screws into its flange or adapter. With an ordinary screw thread, tapering away to a point as shown on p. 221, there is always the chance of crossing the thread when the lens is screwed in. To avoid this either the end of the thread may be milled away as shown on p. 221 or a pilot may be cut. Although such thread forms are refinements, they are well worth while, and it pays to look for them.

TESTING OPTICAL EQUIPMENT

Judging a Lens

To deal with photographic and enlarging lenses in a sound and intelligent way means considering four things.

The first is to know where a lens forms an image. This involves dealing with nodal points, focal points and so on.

The second is to know what faults can affect the quality of the image, and means an acquaintance with lens aberrations.

The third is to know what types have been produced in the way of lens constructions seeking to eliminate or minimise the aberrations.

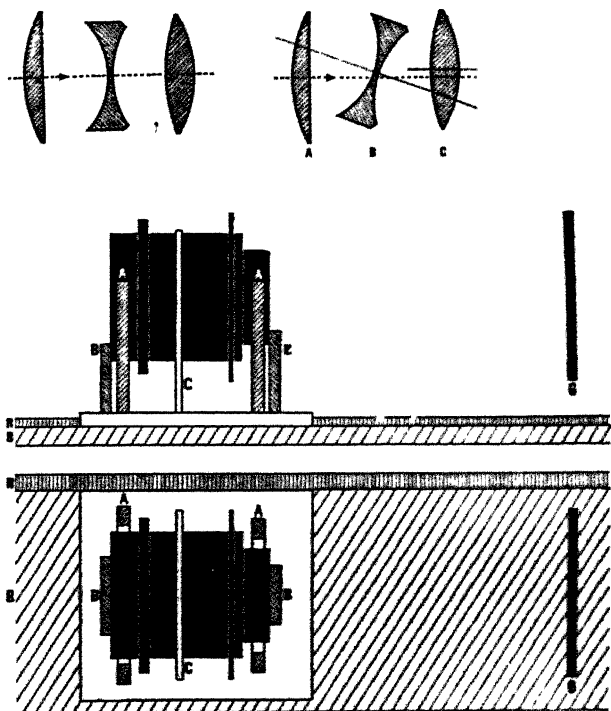
The fourth is to be able to test the lens for its performance and so to assess its value and usefulness.

The first three of these have already been dealt with, and it remains to deal with the fourth, namely the practical testing of a lens.

This testing refers to both new and second-hand lenses, but a few words about special precautions that should be taken with the latter will not be out of place.

Centring

The construction and final assembly of a photographic or enlarging lens is one of the most precise and exacting of light engineering operations. The metal work of the mount and the glasswork of the lenses contained in it have to be so constructed that the vertex of every glass surface is on the lens axis. What exactly this means is shown on p. 225. This shows a perfectly adjusted lens with every glass element just as it should be, and on the other hand a lens in which the central flint glass is both displaced laterally and cocked over and the back crown glass is displaced laterally from the lens axis. The lens that is out of correct adjustment is usually spoken of as being out-of-centre, and the process of



Top left : A correctly centred lens (p. 224).

Top right : The ways in which a lens may be out of centre are shown in an exaggerated form. The central lens *B* has its centre removed from the expected lens axis, and at the same time the lens is cocked over. Lens *C* is displaced laterally from its correct position (p. 224).

Bottom : An improvised arrangement for testing centring is shown in plan and elevation. The aim of any arrangement of this type is to support the lens in such a way that it can be focused and kept in focus while it is turned as smoothly as possible about an axis coincident or at least parallel to its own axis. The quality of the image is examined as the lens is turned round both when the image is in the centre of the field and away from this central position. If the lens is exactly centred there is no change in the image as it is turned in its supports (p. 228).

CHECKING THE LENS CENTRING

bringing it to a perfect state is spoken of as *centring* the lens, and the lens is then *centred*.

Alternatively if some of the glasses in a lens are not in exact adjustment, it is possible to remedy the effects of this by careful adjustment of one or more glasses specially mounted in the lens so that this can be carried out. In this case although the individual glasses in the lens are not centred the effects they produce cancel one another out, and the lens as a whole behaves very closely as if the glasses were all perfectly centred.

In either case the adjustments have to be carried out to very close limits, usually within a few ten-thousandths of an inch, say to within .0004 inch. The test of centring sometimes given in accounts of lenses, namely to see that all the reflections of a lamp or candle-flame are in a straight line is useless in the hands of an amateur, except in the very crudest cases where the lens is only fit for the junk-box.

In exactly the same way the separations between the glasses in a lens are fixed within very close limits. Changing the separation of glasses by .002 inch in a 5 inch wide-angle lens may ruin the performance, and there are other lenses even more sensitive.

What this means in practice is that one should shun like the plague any second-hand lens which seems to have been in any way maltreated as far as its mounting is concerned. Screw threads that have been bruised, metal shoulders that have been damaged, lens bodies that have been strained, lock-rings inside the lens mount that have been officiously loosened and then tightened again, all these things may upset the centring of a lens. And once this is upset it is no job for an amateur or anyone outside the makers' factory to put it right.

Theoretically a properly centred lens should stay centred always. But in practice it is surprising the amount of maltreatment that lenses may receive, some of which can be hidden by a judicious coat of lacquer, but other aspects of which can very well produce bad definition.

Testing the Centring

With a second-hand lens, unless backed by a reliable guarantee or the reputation of a leading trader, it pays to be cautious about the centring of the lens. And as testing for centring helps to decide whether any faulty and uneven definition is due to the lens or maladjustment of the camera, it is of much more than academic interest to deal with it at greater length.

Tests for centring are most easily carried out with a star. This is just a small hole in a piece of metal sheet or card illuminated from behind, preferably by a half-watt pearl bulb, with a current consumption of about twenty-five watts in a normal case. The distance of the star from the front of the lens should have a minimum value of twelve to fifteen feet, and the diameter in this case should be between one-twentieth and one-tenth of an inch, according to individual taste. If possible it is worth trying both sizes, and others on the larger and smaller sides to see which one seems to show up the lens performance most clearly in any individual case. To give the maximum information about the centring the pinhole should be as small as is consistent with enough light getting through to make its image easily visible.

The lens being tested is used to form an image of the star on a ground glass screen, with a very fine greyed surface, and the image is examined with a high power focusing magnifier such as that listed by Dallmeyer, or any equivalent magnifier with a magnification of round about 10 to 15 diameters. The screen is used with the ground surface towards the lens, and the magnifier should be carefully focused through the glass on to this ground surface. This is most easily done by drawing fine pencil lines on the ground surface and focusing on them. Accurate focusing of a magnifier is essential, of course, in all cases where the image on a screen is being examined critically, as in focusing a lens.

A rough idea of the lens centring can be obtained by using the focusing screen that can be fitted in almost every camera.

and focusing the star image on this in the centre of the screen. Then take the lens slightly inside and slightly outside its position of best focus. The star image should approximate fairly closely to a circular patch of light. If it shows an uneven shape, especially with a pronounced flare away even when the image is in the centre of the screen, then it should be rejected at once as being badly out of centre.

A concrete example of the way in which a testing camera may be improvised, and the way in which it is used to obtain more accurate and reliable results is described below.

The lens may be supported on two V-grooves cut in wood about a quarter of an inch thick and mounted on a baseboard as shown on p. 225. The heights of the V's have to be adjusted in accordance with the shape of the lens mount, and the part of this that they bear against, so that the lens axis is horizontal, within one or two degrees. This can easily be tested by setting a 90 degree square against the front or back of the lens mount and against the baseboard. The bearing surfaces of the V's should be finished as smooth as possible to avoid friction when the lens is turned round, and if possible should be faced with metal.

Once the lens is mounted in this way the further requirements, so that it can be rotated smoothly, are that it should have no fore-and-aft movement on the V's and no tendency to rise on them. These can easily be ensured by mounting stops back and front as shown, and by a rubber band stretched over the lens.

The base-board carrying the lens is made to slide in a direction parallel to the lens axis by keeping it bearing against the runner shown on p. 225. This can also be set parallel to the lens axis with the aid of a set square placed against back or front of the lens mount.

Finally a focusing screen of ground glass is needed which is mounted as shown on p. 225 at right angles to the lens axis, or what is the same thing at right-angles to the runner which guides the movement of the lens carriage.

The image of the star described above is cast on the glass screen and examined with the 10x magnifier.

The Image is focused by sliding the lens carriage backwards and forwards, keeping it pressed against the runner so that the star Image does not wander about. When a suitable focus is reached the lens carriage has to be clamped in position ; very often this can be done quite adequately with plasticine or drawing pins.

The lens has then to be rotated as smoothly as possible. With a little patience this can be done quite easily.

The essential thing in examining the centring of a lens is to examine the shape of the light patch as the lens is turned round. This has to be done both when the star is placed to give the light patch in the centre of the focusing screen, and when the image falls in various positions away from this central point.

(While strictly speaking this method checks the centring relative to the lens body and not to the rear thread as is the manufacturing custom, the discrepancy that this introduces is negligible owing to the methods followed in producing lenses.)

The usual out of focus appearance in the centre of the field is an almost circular patch of light with a fairly bright pip not far away from the centre of this. The pip should not wander violently as the lens is turned round. If it does the lens is out of centre and must be seen to by the maker.

Away from the centre of the field the shape of the light patch is usually fairly complicated, and incidentally an examination of the light patch in this instance will bring a healthy disillusionment to those who imagine that modern lenses are free from aberrations. But no matter how complex its shape the light patch must not change appreciably as the lens is turned round.

With a first-class lens no change at all will be seen as the lens is turned. But with a cheaper type of lens, or with one slightly damaged it is quite likely that a certain amount of change will be seen. Whether it is excessive must be left to common sense. It is impossible to dogmatise, and in any case an ounce of common sense is worth a ton of dogma in

questions of this kind. A lens appreciably out of centre will soon be recognised.

The centre of the field, in what has been said above, can easily be fixed sufficiently nearly by eye as the point of intersection of the lens axis and the ground glass.

Testing Alignment

The ultimate test of any lens is the kind of photograph it produces. And this means that to give a lens a fair test the lens and the plate must be absolutely square on to one another in the camera before any testing is done. Uneven definition as regards opposite sides and opposite corners of the plate may be due either to faulty mounting of the lens in the camera or to the lens being out of centre. The method just outlined enables the quality of the lens centring to be determined. *If the lens is accurately centred then the uneven definition can definitely be traced to the camera and the mounting of the lens in it.* To remedy this type of defect is a job for an instrument mechanic, and can often be done in the repair departments of the larger traders. If the lens is out of centre the re-centring is a very highly specialised job and must be left entirely to the lens manufacturer.

There are other faults that may arise in a second-hand lens, and that should be completely absent automatically in the case of a new lens from a reputable maker. They include such things as damage to the cementing of two glasses, for example the rear pair in a Tessar construction, strain in the glass through amateur tightening of a lock-ring, and softening of focus due to scratches on the lens surfaces. All of these show up in a star test.

Another casual defect that should be looked for with a second-hand lens is the existence of reflections from metal surfaces inside the lens mount. In the lens as it leaves the factory all internal surfaces are very carefully blacked with a special paint. In the majority of cases this blacking is quite permanent, but owing to the treatment that it has received it is possible for a lens to display these surfaces in an un-

blackened state. They do not produce effects that are easily seen in a star-test except by an expert. They should, however, be looked for as they can cause considerable trouble with the light that they scatter. A lens in this condition is best returned to the makers for attention before it is used on critical work.

It can be stated as an absolute requirement that the out of focus light patch produced as the image of the star should be circular within very close limits when the image is in the centre of the field, and that the light distribution should be fairly even. There should be no spikiness or general wooliness of definition.

Staining

The stains or bloom on the surface of a lens a few years old are in no way a defect, and there is no reason apart from improving the general spick-and-span appearance of the lens why they should be removed. The only good way of getting rid of them is to have the glass surface repolished by the maker. It needs fairly drastic treatment to get rid of them otherwise, and this is very likely to leave its mark in the form of a host of minute scratches. Each of these scratches diffuses and scatters part of the light falling on the lens, and the damaged surfaces really constitute an efficient diffusing screen built into the lens. Some glasses bloom much more readily than others, but if the surfaces of a lens a few years old are gleaming like crystal it is worth while looking at them closely for a myriad of tiny scratches. These stains are of essentially the same nature as the colour given to a surface by surface treatment, described later (page 286); they do not impair the definition and they actually increase the light transmission.

The staining described above must, however, be distinguished from another type that is less frequently encountered. This latter gives not a bloomed effect to the surfaces of the lens but a *frosted* effect. The lens surface then seems rather grey and milky, like very thin ground glass.

It is encountered mainly in lenses that have been subject to rather extreme atmospheric conditions, such as prolonged exposure to sea air, or to the abrasive action of flying dust and sand. This type of surface degradation should be removed by repolishing the lens : It softens the definition considerably.

The above remarks have been made with special reference to second-hand lenses, in which a considerable trade is done each year, but they have a bearing on the testing of new lenses. The testing methods to be described below are concerned equally with new and used lenses (apart from the checking of focusing scales described in the next section), but whereas it is possible to regard the testing of new lenses as in some ways a luxury—although as far as the serious amateur or professional is concerned this does not hold—with used lenses or those from doubtful sources of supply it should be regarded as a necessity.

Testing the Optical Performance

The defects dealt with in the previous sections can be classed as "casual" faults. They are not inherent in any type of lens, but arise because of individual troubles with the lens mounts.

The other defects that have to be dealt with are the "inherent" faults. With a lens of useful aperture and field the aberrations of all kinds come crowding in, as described on pages 94 ff. With only a finite number of lens curves and thicknesses to be used to correct the aberrations a compromise must be reached, and the correction of some aberrations has to be sacrificed slightly to obtain a better correction of others. All the aberrations cannot be removed, and those that remain in any particular design give it a characteristic performance. The flaws in definition arising from the residual aberrations do not vary from individual lens to lens. They are inherent in the type of lens in question.

From the account given above of all the aberrations that may afflict a lens, it follows that to test a lens to see

how good it is, or to compare two lenses, is a job that can be tackled most easily in four main stages, with only some minor points to clear up after that. The four main stages are to deal with :—

- (1) Central definition.
- (2) Chromatic effects.
- (3) Definition away from the centre of the field.
- (4) Distortion.

The central definition and some allied topics are dealt with in the next section, and the other subjects in the following sections.

Central Definition

The easiest way in which to deal with the definition in the centre of the field is by a star test as already described. The ultimate testing of any lens has to be done by taking a photograph with it, but quite a lot can be done especially as regards central definition with a star test which may be rigged up very easily and quickly. All that has to be done is to focus the small illuminated hole on the ground-glass focusing screen that can be fitted in practically every serious camera, and see what this image is like when examined with a high-power magnifier. It also pays to examine the form of the image when the lens is slightly inside or outside its exact focusing position.

The factors that may affect the central definition are spherical aberration (page 103) and axial chromatic aberration (page 122), both of which can be seen to a greater or less extent in the quality of the star image.

With a lens very well corrected for both these faults the edges of the star image are sharp and clear cut and come into focus crisply and suddenly. When there is an appreciable amount of spherical aberration present the edges of the star become rather blurred and the star itself may be surrounded by a tenuous halo. There is no longer the sudden snap into focus, but all that can be obtained is a position where the image of the star is cramped into the smallest

compass. This position cannot usually be fixed as easily or certainly as can the position of focus with a crisp image. There is a certain vagueness introduced about the position of focus. Practically every photographer will have seen this kind of thing in practice. Some lenses are easily focused with absolute certainty. Others are difficult to focus, and when focused always give the impression that the position may not after all be the best focus. This effect is due to the amount of spherical aberration present, either under- or over-correction, or zonal aberration. It shows up very clearly indeed with a star test.

It cannot be taken for granted that axial chromatic aberration will be seen with a star test, but there are instances where it shows up. What happens then is that the star image has either a red or a greenish blue edge, or more rarely that it has a rather pronounced blue halo.

Any other defects in the star image, such as a bright spike of light thrown out, a series of bright and dark rings in the light patch, or an out of focus image consisting of a bright ring of light with a dead black centre are casual faults that can and should be rectified. They are quite distinct from ineradicable features of the star image due to aberrations in the lens.

Change of Focus on Stopping Down

One other thing that should be tested for, especially with high-aperture lenses and simple wide-angle lenses of the type described above, where the lens is focused at one aperture and the exposure made at another, is the change in focus of the same object with decreasing lens aperture. The focus actually used in any specific case is that where the bundle of light rays is smallest, and this depends on the lens aperture and the amount of spherical aberration in the particular design of lens. It is shown up easily in practice by focusing on the star with the lens at full aperture, then focusing with the lens stopped down and noting the difference if any.

Change in focusing position cannot always be avoided,

although as a rule it is at the most of the order of a hundredth of an inch or so with a 5 inch lens, and the fact that it can be detected is no definite and automatic reason for rejecting a lens. But if two lenses are being compared it is worth looking out for this point.

Focusing Scales

The last application of the star test, because of the ease with which it allows of precise focusing being done, is in checking over focusing scales on a camera, or the focusing movement on a lens in a focusing mount. All that has to be done is to place the star at different distances from the camera, move the focusing arrangement to these distances and see how closely the star is in focus. A few inches tolerance should be allowed on the setting of the star as it is often not evident whether the distance is to be measured from the front of the camera, the front of the lens, the forward nodal point, or the focal plane. Testing the focusing movement is more important with a second-hand than with a new lens or camera. If any play in the movement is found in a lens mounted in a focusing mount, it should be set at various positions and the star focused on the screen. The image should then be examined in each of these positions to see whether during the course of its focusing movement the lens remains square on to the plate.

The adjustment of focusing scales just described does not apply to non-achromatic lenses such as are found on the cheapest types of camera. The adjustment then is a rather more complicated affair necessitating allowances for chromatic effects and field curvature, and is best left entirely to the camera manufacturer.

There is one further application of minor importance to which the star test can be put, and that is to test a filter (page 273). Focus the star on the ground glass without the filter. Then put the filter in front of the lens and re-examine the star image. The quality of the definition given when a poor filter is used will explain better than any words

the wisdom of getting a really first-class filter, optically worked and polished. A second-rate filter brings even the best lens down to its own level, and this can be seen very clearly indeed with a star test.

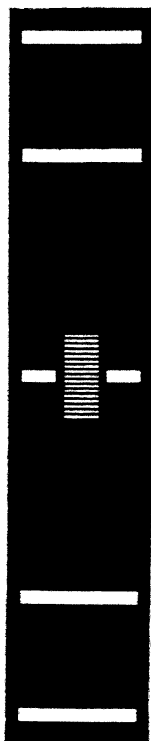
Chromatic Effects

It has already been mentioned that in some cases the presence of axial chromatic aberration makes itself known, especially with a heavy secondary chromatic spectrum in the lens, when a star test is made. It shows up as a red or greenish fringe round the star image, or a blue halo round the image. These colour effects, especially in so far as they deal with blue light, can be seen most clearly by replacing the half-watt bulb in the star by a photo-flood bulb.

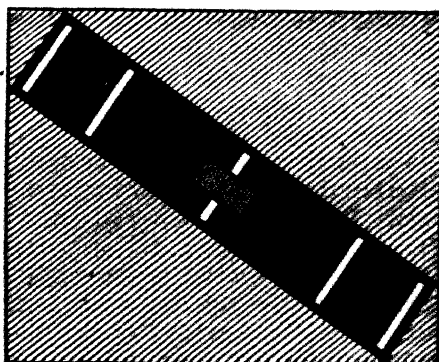
Even if the axial chromatic aberration cannot be seen in a star test using a photo-flood, it should not be assumed that it is absent as far as its effect on the photographic plate is concerned. The eye and the sensitive plate respond to different colours to widely varying degrees.

Lateral Chromatic Aberration

The other colour effect, the lateral chromatic aberration, can also be seen in a star test with a photo-flood bulb. The camera is aimed so that the star image is near the corner of the ground-glass screen. The image is focused and examined with a high power magnifier. *When there is any appreciable amount of lateral chromatic aberration present one side of the image has a red fringe, and the other has a deep blue fringe rather wider than the red one.* With panchromatic material this shows up as a blurring of the definition. The further away from the centre of the field the greater the spread of the red and blue fringes, and the greater the blurring of definition and falling off in performance. With colour material the lateral chromatic aberration can become particularly troublesome. It gives coloured edges to all objects away from the centre of the field.



Left : The type of chart that may be used to test for lateral chromatic aberration (p. 236).



Above right : The way in which the image of the chart should cover the negative or focusing screen. The lens is focused on the fine lines in the centre, and a photograph taken on colour film. The images of the flanking lines are then examined for coloured fringes. Each has either a blue or a red fringe outside when there is lateral chromatic aberration, and the fringe is more pronounced on the outer set of lines (p. 238).

TESTING LATERAL CHROMATIC ABERRATION

As far as lateral chromatic aberration is concerned it can be dealt with quite satisfactorily by a star test using a photo-flood. If any additional check is needed, especially if the lens is to be used extensively with colour stock, this can be done by photographing an easily made chart, on colour material.

The aim of the chart is to provide a white line on a black background which can be photographed. A simple form is shown on p. 237. The line is produced most easily by pasting black paper on matt white card or heavy paper already fastened to plywood, braced if necessary to prevent it warping. The lines should be about .15 inch wide and photographed at a distance of about 10–15 feet from the lens with a lens of 5 inches focus or lens. With longer focus lenses a few trial and error attempts will soon show the width of line to use. The chart size has to be fixed so that its image on the plate covers the diagonal as shown on p. 237. The way of doing this follows from the discussions on pages 46 and 58.

The resulting picture should be closely scrutinised to see whether there are coloured fringes on the images of the lines. The symmetry of any fringes obtained, so that the fringes are in all cases red inwards and blue outwards or the other way round, and the way in which they become more noticeable with the outer lines, show that they are definitely produced by the lens and are not casual defects.

There is one very important fact to bear in mind, and that is the fact that the lateral chromatic aberration is not cut down or changed by stopping down the lens. It is an effect that is quite independent of the lens aperture, and is just as likely to be found in a small aperture as in a large aperture lens.

Enlarger Lenses : The tests for lateral chromatic aberration just given are intended for photographic lenses. Enlarger lenses can easily be tested for the defect, but they should be tested in an enlarger, under the conditions in which they are to be used. What this implies is the preparation of a test negative consisting of fine transparent lines on a dead black background. The lines should be about .002 inch wide for a 2 inch to 4 inch focus lens, and about .004

Inch for 4 inches to 7 or 8 inches. There are no particularly close limits on the widths of the lines and the values just quoted are a rough guide only. A test negative can be made by photographing the chart described above on a process plate with a lens, already known to be satisfactory, stopped down to an aperture two or three stops below its maximum aperture. The methods given on pages 46 and 58 explain how the chart and camera set up should be arranged to give the required result. An alternative type of test negative can be made by taking a strip of film such as is made to demonstrate the performance of miniature projectors and mounting it so that it stretches across from corner to corner of the area from which enlargements are to be made.

The image on the enlarging board should be very carefully examined for coloured fringes on the lines, especially for a red fringe. This shows up better than the blue fringe. Any lens with a pronounced red fringe should be rejected, it is useless as an enlarging lens. As a rule it is quite enough to test the lens at one degree of enlargement.

Axial Chromatic Aberration

Whereas the testing for lateral chromatic aberration can be done quite well visually with a star test, the final testing for axial chromatic aberrations has to be done photographically.

It consists in focusing on one object in the centre of the field, and photographing a group of objects close to this, some nearer the lens and some further away. A useful group is shown on p. 241. The step-wise arrangement is an additional safeguard against false results being obtained by a slight maladjustment of the camera. Suitable objects can be made by pasting slips of newspaper sub-headings on wooden standards as shown on p. 241. These can be photographed at a distance of about 15 feet. The main thing to settle on is the separations between the various objects in the group.

The general formula, or at least one that is sufficiently accurate for all practical work is as follows : If the distance

of the middle object from the lens is D inches, the separation between objects d inches, and the focal length of the lens F inches, then the separation between the images is given by

$$\text{Image separation} = \left(\frac{F}{D}\right) \times d.$$

For instance with a middle object at 15 feet, a lens of 4 inches focus, and a separation between objects of 10 inches, then

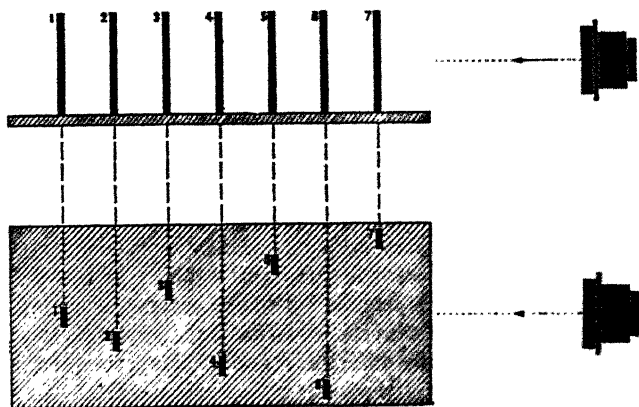
$$D = 180, d = 10, F = 4, \text{ and the Image separation} = \left(\frac{4}{180}\right)^2$$

$\times 10 = .005$ Inch very closely. For a lens up to about 4 inches focus the separation should be between .0015 Inch and .0025 Inch, and for lenses over 4 inches between .0025 Inch and .005 Inch, as a rough rule. As already mentioned definite rules cannot always be fixed, and a little common sense in practice goes a long way. If the separation seems too large or small with a particular lens it is a simple job to repeat the photograph with a varied separation. The values given above will be found useful in very many cases, and a convenient starting point in the remainder.

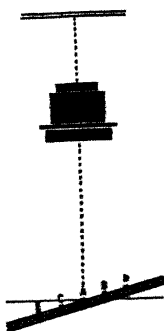
As far as is practicable the photographs should be taken on panchromatic fine-grain stock.

The procedure is as follows : number the test objects from 1 to 7 as shown on p. 241, with No. 1 farthest from the lens. The middle one is No. 4 : focus on this visually with a focusing screen. Then expose a plate and examine the image on it. In the absence of axial chromatic aberration No. 4 will be in sharpest focus, with Nos. 3 and 5, 2 and 6, etc., equally diffuse.

If No. 3 is sharpest, with Nos. 2 and 4, Nos. 1 and 5 equally diffuse there is axial chromatic aberration present. The separation between the visual and photographic images in this case is equal to the separation between the images of Nos. 3 and 4, and the photographic focus is longer than the visual focus by this amount. If No. 5 is sharpest the photographic focus is shorter by this amount. If No. 3 and No. 4 are equally sharp then the photographic focus lies between their respective images.



Above : The arrangement of charts used for testing for axial chromatic aberration is shown in plan and elevation. Each chart should preferably have the same type of pattern on it. One useful form consists of strips of newspaper sub-headings. The lens is focused on number 4 and a photograph taken. Axial chromatic aberration shows up then by giving in the photograph a sharper image of 3 or 5 than of 4 (p. 240).



Above : The axial chromatic aberration of an enlarger lens may be examined under enlarging conditions by using a sloping enlarging board. A negative of an even or repeated pattern should be used. The part of the enlargement at A is brought into sharp focus. The presence of axial chromatic aberration is shown by the image on the print of either B or C being sharper than that of A. A suitable slope of the board is 20-30 degrees (p. 242).

TESTING AXIAL CHROMATIC ABERRATION

What is fundamentally the same procedure can be used to test the correction of enlarging lenses under their actual conditions of use. An enlargement is made with a sloping board as shown on p. 241. To get the best results it should be made from a test negative made by photographing a sheet of newspaper on process plate. The enlarger is focused on the centre of the board, marked A on p. 241, the printing paper inserted, and an enlargement made. If there is no axial chromatic aberration the definition of the enlargement is best at the point A, and equally diffuse at B and C as also marked in the diagram. If the blue focus of the enlarger lens is shorter than the visual focus then the definition is best at B and equally diffuse at A and D. If it is longer the definition is best at C and equally diffuse at A and E.

This test, incidentally, as in the case of the corresponding test for photographic lenses, shows in a very obvious manner the falling off in definition that results from using a lens suffering from axial chromatic aberration. A suitable slope of the enlarging board is 20 to 30 degrees.

A lens that has been used in a satisfactory way in an enlarger with ordinary half-watt lighting should still be checked, as just described, if it is to be switched over to regular use in an enlarger with mercury vapour illumination. Many enlarging lenses will work all right under the new conditions, but there are some that show signs of axial chromatic aberration, and the lens should be examined for this.

Secondary Spectrum : There is one further aspect of axial chromatic aberration to be dealt with and that is the effect of the secondary chromatic spectrum. It is the secondary spectrum that makes it impossible to use a lens achromatised for visual work as a photographic lens. In a photographic lens correctly achromatised for this work the secondary spectrum usually is not very much in evidence even with panchromatic emulsions. But in photographic work where an unusually high quality of performance is required, in process work, and in first-class colour work, it does show up. With black and white photography and with photography as applied in process work the secondary spectrum gives a

slight blurring of definition, appreciable only when the highly critical standards in force in this work are applied. In colour work it shows up as a red or greenish blue fringe round the edges of objects in the centre of the field, especially where indoor shots including such things as electric bulbs or flames are concerned, or anything equally bright. The coloured fringes in this case differ from the colour fringes caused by lateral chromatic aberration in that they are the same colour on both sides of the image, and not as before red on one side and blue on the other.

The testing for the secondary spectrum can be carried out well enough for most purposes by repeating the tests for axial chromatic aberration with blue, yellow, and red filters in front of the lens. Alternatively it can be carried out by photographing a star, as described in the star test, on coloured material.

It is only in rare cases that the secondary spectrum is at all noticeable, and to meet the requirements of these cases there are apochromatic process lenses, and lenses derived from the *Speed-Panchro* type with a specially reduced secondary spectrum. Both of these types have been described in the previous chapter.

Testing the Field

In testing a photographic or enlarging lens the most important thing is to find out what the definition in the field is like, away from the centre of the negative or enlargement.

The central definition and chromatic correction of any photographic lens should be good, and in any case they are easily dealt with by the testing methods described above.

In the design of one of these lenses it is a comparatively simple thing, except in the case of some extreme aperture lenses, to get the spherical aberration and chromatic aberration well corrected. The main difficulty that faces the designer is to get a high standard of definition over the field away from the centre of the negative, in other words

to produce a lens as free as possible from astigmatism and coma of all orders. *The outcome of this state of affairs is that in every case the value of the lens is determined by its performance away from the centre of the field, where the definition it gives is much inferior to its central definition.* And while in comparing lenses or testing any lens the central definition and chromatic corrections should be examined it is of fundamental importance to examine and compare the definition over all the field.

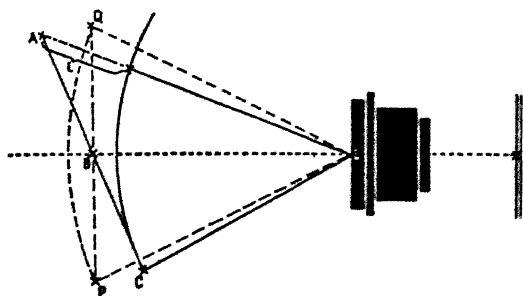
Ideally every point away from the centre of the field, and every line, should be reproduced sharply and clearly as a point or as a straight line. In practice this state of affairs cannot be realised. The aberrations described on pages 102-129 come into play and make it impossible to realise this flawless definition. And it follows from this that these same aberrations, as already described, furnish a very useful guide as to what to look for when testing a lens.

From the account given on pages 110-122 of coma, astigmatism, and field curvature it follows that three types of definition have to be dealt with :

- (1) The definition of a point.
- (2) The definition of a line or edge stretching out like a spoke from the centre of the field.
- (3) The definition of a line running transversely across the radial lines like the rim of a wheel.

Whatever is photographed should preferably show all three types of definition separately. The types of photograph that are sometimes given, showing some picture of artistic merit, are virtually useless as far as a critical assessment of the lens performance is concerned. Rather better is the photography of a chart consisting of printed matter. This shows up in a fairly clear way the quality of the averaged performance of the lens, but is uncritical to the extent that it does not sort out the exact contribution of each type of definition without very careful examination.

When a test of this type is to be made a convenient way of carrying it out is to photograph a sheet of newspaper,



Top : The adjustment of the charts or support square on to the lens can be checked by a string stretched from the lens to points on the chart equi-distant from its centre. When the chart is square on to the lens (as shown by the dotted line) the distances from the lens to points *P* and *Q* that are equi-distant from the centre of the chart *B* (measured along the chart) are equal. If the chart is not square on these the distances to points *A* and *C* equally distant from *B* are not equal. As shown *A* is farther from the lens. The centre of the chart *B* is the point whose image lies at the centre of the focusing screen or film (p. 246).

Bottom : The performance of a lens can be tested by arranging charts on a support so that their images cover the plate or film as shown. A suitable type of small chart for mounting in this way is shown on p. 249.

TESTING CHART ADJUSTMENT

preferably with the kind of typescript and paper texture that one associates with *The Times*, so that the image on the plate is between one-fifteenth and one-twentieth of the size of the original. How to work this out comes directly from the formulæ

One-fifteenth reduction. Distance of chart is 16 times the focal length of the lens.

One-twentieth reduction. Distance of chart is 21 times the focal length of the lens.

Even illumination is an absolute necessity, and is usually best obtained by photo-floods on either side of the camera. *It is also of major importance that the camera and lens should be square on to the chart within close limits.* This can be ensured sufficiently nearly by stretching a cord from the front of the lens to the screen and using this to line up the chart. The centre of the chart is taken as the part that gives an image in the exact centre of the focusing screen. Equal distances from this centre are marked off on the chart and the cord is used to check over that these are all the same distance from the front of the lens. How this works is shown on p. 245. The exact centre of the focusing screen can be found by drawing lines diagonally from the corners of the screen to cross in the centre.

The photograph should preferably be taken on a fine-grain panchromatic material of medium contrast, and developed with a developer that is not too contrasty in its results. A contrasty negative hides especially the coma flairs that are of importance, and that show up when there is not such hard contrast.

As already mentioned even illumination is a vital necessity. This is especially so when two lenses are being compared. In this case also the negatives should be of the same density. It is impossible to compare negatives of different densities in a reliable way.

The virtues of the test just mentioned are that it is easy to rig up with materials at hand, and that it gives a general outline of the lens performance. Its defect is that it is not sufficiently precise for really accurate work, or

sufficiently analytical as far as separating the various types of aberration is concerned.

Testing Charts

To get the best results a chart specially designed for lens testing should be used. There have been several of these described at various times, following more or less logically along the lines laid down by the theory of the aberrations on pages 102-129. But many of these have been rather complicated for actual use outside professional establishments.

As far as testing the covering power of a lens is concerned the necessary results can be obtained by placing small test charts on a wall or other support so that their images cover the field of the lens or the negative as shown on p. 245. They lie along each semi-diagonal of the plate, one-third, two-thirds, and at the end of the semi-diagonal, approximately, with an extra one at the centre of the field. The pattern of each of these charts has to be chosen to show up the various kinds of definition mentioned and to obtain a rough numerical way of describing the performance. A suggested pattern is shown full-size on p. 249.

When arranged on a wall or dark support as shown on p. 245 so that they cover the plate to be used (the size of support and so on can be worked out by the methods explained on pages 46, 58, once the size of plate is known), they are suitable for photographing with lenses up to 8 inches focal length at a distance of 10 feet for all focal lengths of lenses. At this distance the medium group of lines marked *M* give images with a 1 inch lens that are $1/1200$ inch wide, with a 2 inch lens $1/600$ inch, and so on up to $1/150$ inch for an 8 inch lens. The clear spaces between the lines are the same width as the lines themselves. The finer sets give lines with .5, .33, of this separation, and the coarser sets have separations 1.5, 2.0, and 2.5, times that of the *M* set. The circular dots give images with the same diameter as the width of the medium lines.

Charts should be made up which are both positive and negative copies of the chart on p. 249 and photographed under the same conditions as for a newsprint chart.

The images of the circular dots in the negative charts, i.e., of white dots on a black ground, when examined with a high power magnifier, show some of the aspects of definition of a point object. They show up anything in the way of coma flairs and any spread due to lateral chromatic aberrations. Other important aspects, in particular the contrast afforded by the lens, are shown by examining the images of circular dots in the positive copy. In the presence of excessive aberrations the light encroaching from the white surround may be sufficiently intense to wash out the dot images completely.

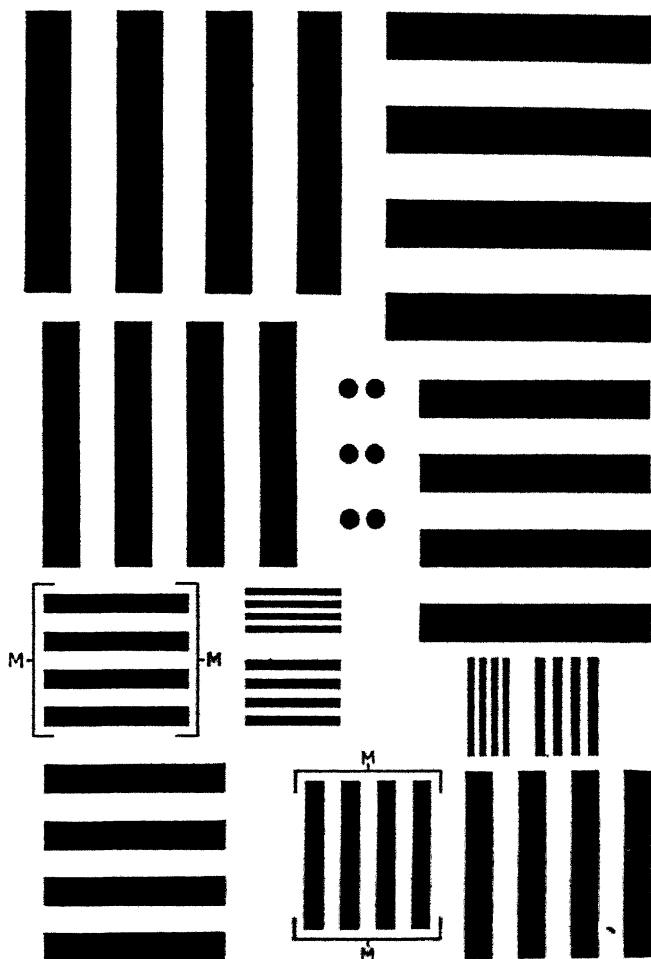
Resolving Power

The quality of the definition of the lines gives an idea of the "resolving power" of the lens, and it may be opportune to say something at this stage about resolving power.

The idea of resolving power originated in astronomical work, with the idea of specifying how far apart two stars must lie so that they could be distinguished from one another, with the telescope whose resolving power was under consideration. What this involved essentially was the separation of the images of two points, so that it could be inferred that there were two stars and not just one producing the light patch.

With photographic lenses the term resolving power has come to mean for the most part the separation that must exist between the images of two equal lines, with the space between them equal to the width of the line, before the two images can be distinguished on a photographic plate.

Suppose for instance that on a photographic plate with a given lens the closest lines that can be separated are .005 inch wide, with spaces .005 inch wide between them, then one hundred lines and spaces of this width each could be drawn in the space of an inch, and the resolving power of the lens can be described in this case as "one hundred lines



The form of chart that may be used for testing the performance of a lens in the field, and getting a rough idea of its resolving power. The chart as shown is black on white. By making a full-size negative of this a rather better type can be produced consisting of white lines and dots on a black ground (p. 247).

LENS TESTING CHART

per inch." With closer spaced lines the spread over of the images due to the aberrations and diffraction means that it is impossible to say that there are on the plate the images of two distinct lines. In other words the closer-spaced lines are not resolved.

What is important for photography is the resolving power of the lens and film combination. The ability of the lens to separate close detail is determined by the aberrations present, and the ability of the film to record detail is determined by its graininess. Typical resolving powers for different sensitive materials are given in Table XXXI. These figures relate to resolving powers determined under the most favourable conditions of exposure and development. These same factors and the contrast of the target lines must be taken into account in determining the resolving power of a lens-film combination; and in comparing two lenses the conditions must be standardised as much as possible.

The resolving power of a lens may be measured by using a microscope to examine the image of a test chart. This is sometimes referred to as the *visual resolving power* of the lens. The resolving power of the film is measured by forming a test chart image on it with a microscope objective. A useful rule given by A. H. Katz is that *the resolving power of lens-film combination is equal to the product of the lens and film resolving powers divided by their sum*. Thus if the lens has a resolving power of 3000 lines per inch and the film a resolving power of 1400 lines per inch, the resolving power of the lens used with this film is $(3000 \times 1400) \div (3000 + 1400) = 955$ lines per inch.

XXXI.—RESOLVING POWER OF VARIOUS EMULSIONS

| <i>Emulsion</i> | | | | | <i>Resolving Power in Lines/inch</i> |
|---------------------------------|-----|-----|-----|-----|--------------------------------------|
| Verichrome Roll Film | ... | ... | ... | ... | 1100 |
| Super-XX Roll Film | ... | ... | ... | ... | 1250 |
| H.P.3. Roll Film | ... | ... | ... | ... | 1250 |
| Panatomic-X Roll Film | ... | ... | ... | ... | 1400 |
| Super-XX 35 mm. Film | ... | ... | ... | ... | 1400 |
| Plus-X 35 mm. Film | ... | ... | ... | ... | 1750 |
| Panatomic-X 35 mm. Film | ... | ... | ... | ... | 2150 |
| Slow Process Plate | ... | ... | ... | ... | 3750 |
| Kodak Maximum Resolution | ... | ... | ... | ... | 30000 |

This is an approximate rule only, but it serves as a very useful guide to establish the overall performance of lens and film. To determine the optical resolving power photographically it is normal to employ a film or plate having a high resolving power, such as a process type plate or film, as the conditions are not so critical as with faster emulsions which have a lower resolving power. In every case where an optical resolving power is determined, the sensitive materials used should be stated.

It is important in all cases to get an idea of the resolving power of the lens over the entire field it has to cover and not just in the centre of the field. There is also a further point to notice. Because of astigmatism there are two types of definition and resolving power away from the centre of the field, one for radial lines and one for tangential lines; these are quite distinct.

A lens should not be judged by its resolving power only. This latter provides a compact and useful description, but not necessarily a complete one.

Attention must be paid not only to resolving power but to the rendition of contrast. Examination of the images of negative reproductions of the test chart shown on p. 249 will give the resolving power, and an examination of the images of positive reproductions of the test chart will show the reproduction of detail contrast.

Taken together they provide a useful indication of lens performance.

Resolving power measurements are usually carried out on black and white material because of the lower resolving power of colour stock. If a lens is to be used extensively for colour work a series of tests should be run on black and white stock with tricolour, blue, green, and red filters in front of the lens.

Enlarging Lenses : To test the field of an enlarging lens one useful procedure is to photograph the test chart on *Ilford H.R.* or *Kodak Maximum Resolution* at a distance of

10 feet or so with a lens of about the same focal length as the enlarging lens.

This photographing lens should be of the highest performance available to the worker and stopped down to two or three stops below its largest aperture to get the maximum definition. And finally the negative should be scrutinised with a low power microscope to make sure that a clean and clear cut negative has been obtained, with every line crisply defined.

If this cannot be achieved the chart should be photographed at a great distance with a lens of correspondingly longer focus, so that the thicknesses of the lines are about the same as those which the shorter focus lens would give. The angular field covered by the longer focus lens is smaller when it is producing the size of negative that the shorter focus lens would cover, and it has consequently a better chance of giving a clean negative.

An enlargement of this negative will show the quality of definition of the enlarging lens.

An alternative method that can sometimes be applied is to take a photograph with the lens under test of printed matter such as newsprint or a page of a book, with the distance of the print from the lens equal to the distance of the enlarging board from the lens when the degree of enlargement is one of interest.

Make an enlargement of the negative with that degree of enlargement already referred to and then compare the enlargement with the original. They are the same size when the procedure just described is carried out, and comparison is easy.

If a photographic lens is being used in an enlarger it is best to give it a series of tests at varying degrees of enlargement, from one-to-one copying size up to about eight times enlargement, as these types have a tendency to fall off appreciably at the lower degrees of enlargement.

The minimum distance at which any test of a photographic

lens should be carried out is 15 to 20 times the focal length. The definition then obtained differs but slightly, and as a rule inappreciably, from the definition with an object at infinity. This cannot be guaranteed for shorter distances.

Distortion

The main tests that should be carried out in judging or comparing lenses have been described. What remain are more or less tests to clear up some smaller details.

The first of these is distortion. What it means and the effects it produces have been described on page 119. The amount present in any good modern lens is not at all troublesome. There is usually some present, but in a negligible amount for most purposes. Where it would prove most troublesome is in a wide-angle or a telephoto lens, especially a variable power telephoto, and it is worth looking for it in some of these cases.

The easiest way of testing for it is to photograph three plumb-lines of whitened or chalked string hanging against a black background. They are arranged at about 10 feet from the camera and spaced to cover the plate as shown on p. 255. The camera can be squared on to them exactly as was done with the test chart in the previous section. The lens should be stopped down by one or two stops to pick up the definition somewhat (distortion does not depend on the lens aperture), and focused on the centre plumb-line.

A straight edge placed alongside the images of the outer lines will soon show any appreciable distortion by the bending of the line away from the rule. A check made by placing the straight edge against the centre line, which should be dead straight, will show that any curvature is not caused by distortion or buckling of the plate or film in the camera but is a true lens defect.

Vignetting

The remaining tests are not concerned with flaws arising

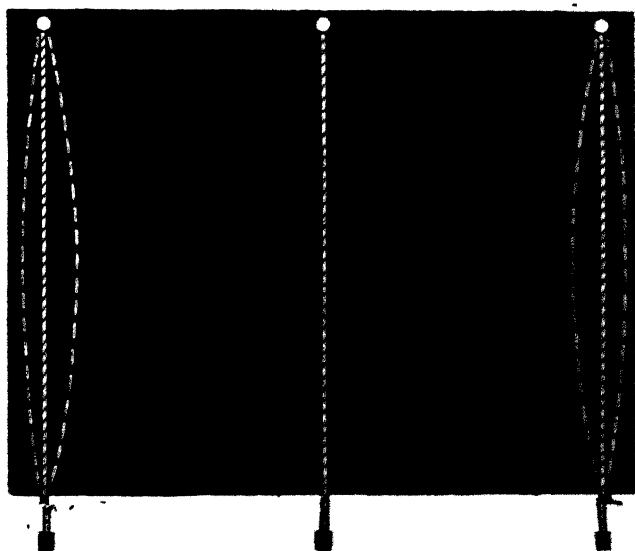
from aberrations but with other minor types of defect that may be present.

For instance it has already been pointed out that it very often happens that the definition at the edge of the field is rather better than the definition in the intermediate zones of the field. This is due in part to the astigmatism correction adopted. *But it is also due in part to the fact that the lens aperture is less for rays coming from the edge of the field. This is known as "vignetting" or "window shut-off."* The way in which it arises is shown for a Cooke Triplet type of lens on p. 257. The diameter of the back glass is large enough to allow rays, parallel to the axis and filling the aperture of the front lens, to get through. The same holds for the size of the iris diaphragm aperture. But when the incident rays make an angle with the lens axis the situation is changed, as shown on p. 257, and not all rays hitting the front lens are permitted to get through. They are stopped by the lens mountings.

The vignetting just described shows up sometimes as an under-exposed area at the edge of the plate. The exact amount varies from lens to lens. The longer the lens the greater the tendency to vignetting, for instance vignetting is more pronounced with the Petzval type of lens than with the more compact Cooke Triplet.

It cannot be regarded as a necessity to measure the amount of vignetting in a lens, but all the same it is often useful to compare two lenses from this point of view.

The technique is simple. The lens is set for infinity, either by trusting to the focusing scale or focusing mount, or by focusing it on ground glass. In any case after the lens is set a piece of brass or rigid card is put against the plate or film locating surfaces. In this card are pierced two fine holes about 1/50 inch in diameter; one hole is at the centre of the plate and the other at the end of a diagonal, in the corner of the plate. If the hole is pierced in metal it should be counter-sunk so that it will not contribute any cut-off of its own to complicate the vignetting effect of the lens, or even make it impracticable to measure this latter. Behind the card or



Distortion in a camera lens can be checked by photographing whitened plumb lines against a black background, or vice versa. In the presence of distortion the side images are bent. The side images are either both convex towards the centre, so that the images have a "waist", corresponding to pincushion distortion, or both concave towards the centre so that the images of the lines bulge outwards in the case of barrel distortion. It is essential in making this test that the centre line should be straight. Any curvature of this means that the plate or film is not flat or correctly supported, and no reliance can be placed on the result (p. 253).

TESTING DISTORTION

brass is placed an electric bulb, shaded so that the only light escaping is that going through the fine holes. The light from each of these holes emerges from the front of the lens as a parallel beam, one beam parallel to the lens axis, the other making an angle with it.

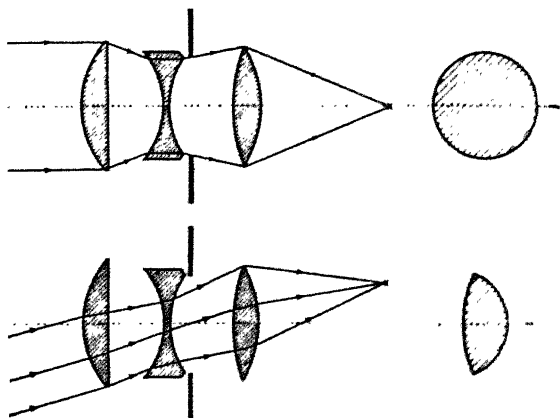
The corner hole is temporarily blocked. A piece of sensitive paper is then put over the front of the lens. The bulb is switched on long enough for the rays from the centre pinhole to make an impression on the paper which will develop readily. The same procedure is then followed with the rays coming from the corner pinhole alone.

On developing the paper it will be found that the rays from the centre pinhole give a circular patch, but the rays from the corner pinhole give a patch of light of the shape shown on p. 257, showing that only a smaller portion of the lens aperture can be used by rays going to or coming from the edge of the field. The ratios of the blackened areas in the two cases can be taken as a measure of the vignetting of the lens.

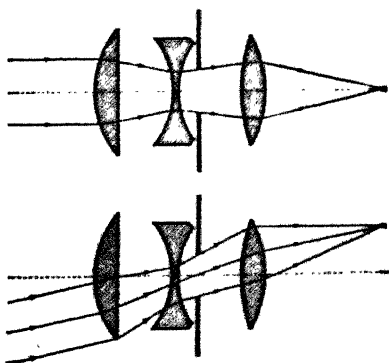
Incidentally this method can be used to make sure that a lens hood is not cutting off light going to the corner of the field. The test just described is carried out with and without the lens hood in place. Corresponding areas should be equal, although the edges may not be so sharply defined with the hood in place owing to the increased distance from the front lens, and the slight divergence of the beams due to the necessarily finite size of the pinholes. If the area is smaller with the hood then this is cutting down the light to the corners of the plate, and should be shortened.

When the lens is stopped down the size of the iris aperture is the governing factor, and the effective vignetting is reduced. The beams that get through are more nearly the same size. This is shown on p. 257. It can be checked up by the method described above.

Incidentally this procedure allows a check to be made of the correctness of the f -numbers engraved on the mount. Divide the focal length of the lens by the diameter of the light patch obtained with the central hole. This gives the f -number.



The rays of a parallel beam of light (top), parallel to the lens axis, going through the lens at full aperture are mainly restricted (except in some very special cases) by the edges of the lenses and the metal of the mount. The same is true for a beam inclined to the lens axis (lower), but in this case the restriction is more severe. The cross-section of the axial beam is a complete circle (top right). With the inclined beam (lower right) only a fraction of the aperture is used and the cross-section of the beam is smaller, as shown (p. 254).



When the lens is stopped down the beam limitation is effected mainly by the iris diaphragm and the restrictions are about equally severe for axial (upper) and inclined beams (bottom) and more nearly the same proportion of the aperture is used in each case (p. 256).

VIGNETTING

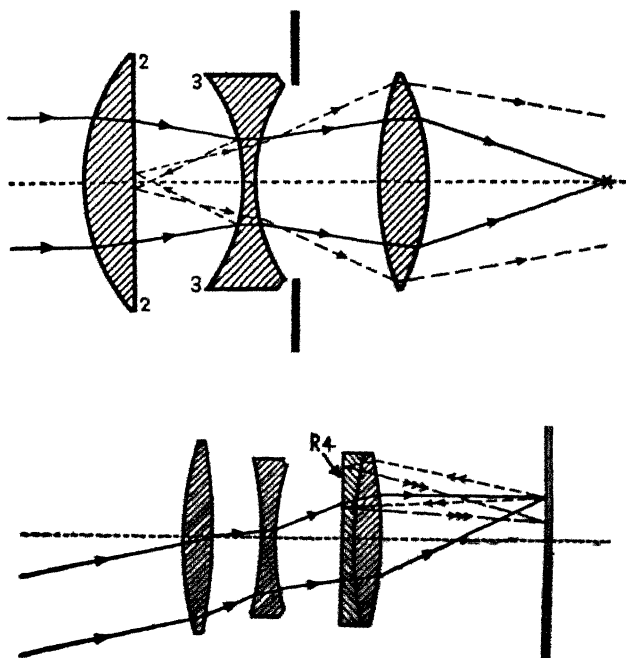
Flare

The last trouble to be dealt with here is the formation of ghosts or of flare.

A certain amount of light is reflected at each lens surface. Light undergoing two reflections as shown on p. 259 reaches the plate or film. And since it has not been through the regular or routine series of bendings it is unlikely that it will come to the focus that it should reach. This happens with rays from all bright points in the field.

When these rays that have been reflected give an even distribution of light on the plate all that happens is that the contrast is impaired somewhat. The real trouble arises when they come to a focus not far from the plate. What happens with a bright object point then is that it has two images : one is its true image, the other is a rather diffuse and out of focus " ghost image " produced as just described.

Another type of reflection that may on occasion prove troublesome is that from the film or plate itself. Some of the light falling on the sensitive surface of the plate or film is reflected back to the lens. Here it may undergo a further reflection at an air-glass surface and be returned to the sensitive material. As before there are two distinct effects that light returned in this way can produce. If the light following such a path does not come to a focus near the sensitive material it just produces an increase in the overall level of fogging. Of greater importance is the case where it does focus near the plate or film. In that event a ghost image is produced as already described above. The path of rays that may form such an image are shown in the diagram on p. 259. As in the case where two reflections take place in the lens the formation of ghost images is, as a rule, of greater concern than the increase in the level of fogging. And in the same way the trouble is mainly encountered when there is one highlight of particular intensity, such as the sun or an electric bulb, near or actually in the scene to be photographed.



Top : A ghost image is formed by rays which are reflected at two air to glass surfaces in the lens. The rays reflected by surfaces 3 and 2 (in that order) are shown. Ghost images are reduced in intensity by surface treatment. The trouble mainly occurs when the images formed by the rays that have been reflected come to a focus near the plate or film, and a local concentration of light or the sensitive material results. When the images formed are not focused near the film the effect of these reflected rays is to raise the general level of fogging (p. 258).

Bottom : There is another type of reflection that has also to be taken into account, namely one from the film itself. This is not essentially different from that arising purely within the lens itself. The film now plays the rôle formerly played by a glass to air surface. Rays are shown, which are reflected by the film and the air-glass surface R4. Surface treatment reduces the chances of light reflected at the film being returned to the sensitive material by reflection at one of the lens surfaces (p. 258).

GHOST IMAGES

There is no short cut to finding out whether there is a pronounced ghost or flare in the lens. The best way to look for it is to hang a bright pearl electric bulb either inside or outside the field covered by the lens and look for the ghost image on a ground-glass screen. Alternatively a photograph can be taken under these conditions.

Experimental Depth of Field

A few more words about depth of field may not be out of place. The main trouble has been the divorce too often existing between the man who used the camera and the specialist in lens theory, and a clinging to formulæ and standard phrases rather than going to the facts behind them.

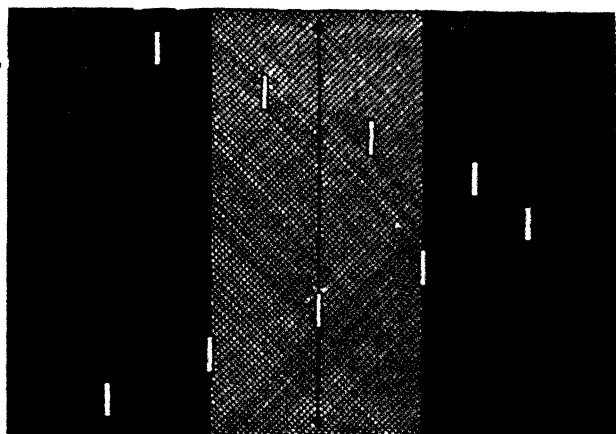
A depth of field chart is in every case only a tool to be used in arranging a camera set up, and not a dogma to be rigidly adhered to. Every man should judge for himself the stages when an out-of-focus object is too diffusely defined, and, on the basis of that, draw up his own depth of field chart, taking into account while doing this the individual way in which the aberrations of his lens will upset the orthodox values of the depth of focus. Photography has to be done with a camera, not with paper and ink in a computing office.

In dealing with depth of field the thing to do is to experiment, to photograph, and then to judge.

The labour and time spent can be cut down appreciably by going about this in the right way.

For every lens aperture there is a hyperfocal distance for that particular lens. Once this is known the depth of field can be worked out in detail, as explained on page 58. *The whole crux of the matter is to find out what is the size of this hyperfocal distance. It can be calculated by making various assumptions. It should be found by practical work, as explained below.*

Set up some of the charts used for testing the field in echelon as shown on p. 261, with the middle chart at 8 feet 4 inches from the lens. Then the set of lines marked M on



An arrangement of charts suitable for experimental depth of field work. The lightly shaded area is the theoretical or calculated depth of field. Charts are arranged both inside and outside the theoretical limits of the depth of field. Charts suitable for this work are of the type shown on page 237. They should be grouped as far as possible so that their images cluster near the centre of the plate or focusing screen (p. 262).

TESTING DEPTH OF FIELD

the middle chart give images on the plate, with the separation of the lines equal to the diameter of the disc of confusion demanded by the theory described on page 59, i.e., .004 inch for a 4 inch focus lens, and so on.

To get the positions of the other charts, work out the orthodox limits of the depth of field as explained on page 65 when the lens is focused on a distance of 100 inches. For instance with a 4 inch lens working at f 5.6 the hyperfocal distance is 715 inches, and the farthest and nearest limits are at 116 inches and 88 inches to the nearest inch, i.e., at 16 inches and 12 inches from the plane focused upon. Set the charts at $\frac{1}{2}$, 1, $1\frac{1}{2}$, and 2 times their distances from the 100 inches plane, i.e., at 108, 116, 124, 132 inches, and at 94, 88, 82, and 76 inches from the lens and photograph them at these distances.

There is one thing of importance that this photograph shows up at once, namely what the same object looks like at various distances out of exact focus. There is an immediate comparison between the way in which detail is reproduced in the sharply focused and out of focus images, even taking into account automatically the fact that the objects beyond the focused position give images reduced in size. Such a comparison of the way in which detail is reproduced is perhaps of greater importance than fixing a size of confusion disc and working religiously to this. It also takes into account the fact that the depth of field may be modified by the presence of spherical aberration as already explained on page 129.

Suppose that the rendering of detail is just good enough at one and a half times the orthodox distance inside the focused distance, i.e., at 82 inches in the example given. Then for working out depths of field for this particular lens aperture it is accurate enough to take a hyperfocal distance $1 \div 1\frac{1}{2} = 2/3$ of the orthodox hyperfocal distance for the nearer limit. It may happen with the same lens, at the same aperture, that the definition of detail of objects outside the focused distance is good at the allowed orthodox distance, i.e., at 116 inches in the example quoted, and not good

enough at $1\frac{1}{2}$ times the orthodox distance, i.e., at 124 inches. A fair estimate would then be that the detail was reproduced sufficiently well up to 120 inches, i.e., to $1\frac{1}{2}$ times the allowed distance given by the orthodox calculation. This can be checked if necessary by a chart placed at this distance. For objects further away than the focused distance the hyperfocal distance to be used in this case is $1 \div 1\frac{1}{2} = 4/5$ of the orthodox distance.

From this experimental point of view it is quite possible for a lens to have two hyperfocal distances to be used as described immediately above. This is due to the spherical aberration in the lens.

There are one or two minor experiments worth trying.

The first is to set up some charts in the field in out-of-focus positions and see how they are reproduced on the plate. In effect, to deal specially with depth of field in the field, away from the centre of the negative.

The second is to make an enlargement of the photograph on papers of varying textures, and to see how the exact reproduction of detail affects the artistic quality of the image with different paper finishes, from glossy to matt and linen finish.

Using a camera to advantage is an art whose technique must be learnt by practice, and a few hours spent experimenting with depth of field photographs is time well spent.

For those who desire an experimentally determined value of the depth of field on the lines of that found on page 59, i.e., with a disc .001 inch diameter for a 1 inch lens, a disc of .004 inch for a 4 inch lens, and so on, with allowance made for the disturbing effect of spherical aberration at high apertures, a rather different procedure must be adopted. The main object again is to get an experimental rather than a theoretical value of the hyperfocal distance, or what comes to the same thing, to see how far out of focus an image must be to give a disc of the proper size.

Again set up a chart at 100 inches from the lens. The M set of lines for any focus lens are the distance apart equal to the diameter of the disc of confusion required, i.e., .004 inch for a 4 inch lens, and so on. When the M set on this chart are out of focus enough for every point on them to give a disc .004 inch diameter with a 4 inch lens (the example will be worked for this focus) then the images of the lines completely invade the spaces and the lines are not resolved.

The chart at 100 inches should be focused on a ground-glass screen and then the focusing setting changed by bringing the lens closer in until the *M* lines are no longer resolved. Suppose that at this position a chart at *D* inches from the lens is in perfect focus. *D* of course in this case is greater than 100 inches, 120 inches say. Then the image of the 100 inch chart is

$$F_2 \times \frac{D-100}{100 D} \text{ inches out of focus, i.e., in this case}$$

$$4 \times \frac{120-100}{120 \times 100} = \frac{16 \times 20}{120 \times 100} = \frac{16}{600} \text{ inches out of focus.}$$

In other words an image, in this case $\frac{16}{600}$ inches out of focus, beyond the plate is the proper diameter, .004 inch for a 4 inch lens. Hence the hyperfocal distance within a few per cent is

$$\frac{100 D}{D-100} \text{ inches}$$

i.e., in the given case $\frac{100 \times 120}{20} = 600$ inches, and all calculations for objects nearer than the focused plane are carried out with this hyperfocal distance.

Similarly the lens can be moved further away from the plate until the chart is no longer resolved. Suppose then that a chart *d* inches away is in focus. The hyperfocal distance for objects farther away than the focused plane is, within a few per cent,

$$\frac{100 d}{100-d} \text{ inches}$$

Finer or coarser standards can be imposed by using the sets of lines flanking the *M* lines. The hyperfocal distances have to be found for each lens aperture, except that the orthodox calculation can usually be relied upon in this case when the lens is stopped down by two or three stops, as already mentioned on pages 132-133. Hyperfocal distances for the performance in the field can be obtained by putting the 100 inch chart in the field and repeating the above, with the distances *D* and *d* judged for charts in the centre of the field. The work is exactly as described above, but it is doubtful whether it is worth carrying out in this case unless it is done for a number of different positions in the field to get an idea of the average performance.

Throughout the formulæ have been given, not with pedantic accuracy but in the simplest form compatible with the accuracy expected in photographic work.

The Care of Lenses

The surfaces of the glasses that make up a lens are carefully polished so that all surface pits and scratches are removed. Where necessary the glasses are cemented together with Canada Balsam so carefully that the junction cannot be detected. Finally they are assembled in the mount and lined up within very close limits.

Perhaps some of the care lavished in polishing the surfaces is expended with the aim of producing an aesthetically satisfying article. But for the most part it is necessary to ensure the highest standard of optical performance.

A scratch on the surface of a lens scatters light, and in consequence tends to impair the definition. One small scratch on its own will not do much harm, but if there are a number, if the surface is covered with a network of fine scratches the definition of the lens will be ruined.

Dirt, and especially grease, on the surface of a lens also tends to diffuse light, and a finger-print on the polished glass will soften the focus of the lens in a very pronounced fashion.

The logical thing then is to prevent as far as possible the chance of dirt getting on the lens. This means that when it is not in use the caps supplied by the makers should be fitted to the lens.

Loose dust and small fragments of grit should be removed with a small camel-hair brush, and no attempts at any other form of cleaning should be made until these have been removed in this way. Optical glass is not really a very hard medium and it is easy to score it with an abrasive fragment of grit. If any particles adhere to the surface it means that they are bound by grease, and a brush moistened with industrial alcohol will help to loosen them. It is very rarely that such a treatment is needed.

The best way of removing grease from a polished lens surface is to rub it gently with a soft linen cloth moistened with industrial spirit. It is essential that the cloth used for this purpose should be both soft and free from grit and dirt. A well-washed linen or silk handkerchief is very useful for this purpose. To get into the corners where the glass meets the metal of the mount the moistened cloth can be wrapped round the end of a pointed bit of wood.

In no case need any pressure be exerted on the glass surface, nor should any be applied.

When grease has been removed the surface may be given a final polishing with a silk handkerchief or with a dry chamois leather.

In no case should any attempt be made to polish the surfaces of a lens with any cleaning material intended for household use, nor scrubbed with soap and water.

A word may not be out of place about the stains that are found on some lens surfaces a few years old. These are not a deposit on the surface of the glass. They are formed by the action of moist air and the chemicals in it, which attack the glass and dissolve out some of its constituents to a depth of about five millionths of an inch. What is then left is a film of silica that closely resembles fused quartz and is about five

millionths of an inch thick. The stains are produced by this silica film in the same way that colours are produced by a thin film of oil floating on water. The film can only be removed by repolishing the surface showing the staining. It is most decidedly not a job for the amateur, and no reputable repair shop will tackle the job themselves. There is no reason really why these stains should be removed. They increase the light transmission slightly, and do not affect the definition of the lens. They are due to a surface formation of the same type as that which is produced by one form of surface treatment. (See page 284.)

These forms of staining must of course be distinguished from the alternative types described on p. 231. These latter are in the main produced by the abrasive action of flying grit or sand, although they may be caused by extreme chemical action, for instance if the lens surfaces have been subject to the action of acid fixing solution in a dirty dark-room. They are definitely capable of spoiling the definition given by a lens and should be removed by repolishing the lens surface. This is certainly a job for the factory, an amateur attempt may result in the cure being worse than the disease.

It should scarcely ever be necessary to clean the inside surfaces of the lens, but if it is necessary the same precautions and methods should be followed that have already been described.

Queries are often raised concerning *bubbles* in the glass from which lenses are made. Bubbles are found in the glass of even the best and most expensive lenses: they are nothing to worry about and do not serve as a valid excuse for adverse criticism of the lens. The glass supplied by the leading manufacturers, English, French, American and German, does not differ in its properties to any significant extent according to the source of its origin. Among these properties is the uniformity of its refractive index, its resistance to weathering and its freedom from bubbles. In making a lens care is taken that none of the bubbles breaks through the polished surface and forms a pit filled

with polishing medium. Bubbles in the body of the glass scatter a small, and in general negligible amount of light. Care is taken that an undue number of bubbles are not present in the glass used, but a small number cannot be regarded as a significant fault or serious blemish. They have no influence on the lens performance.

If bright markings appear on the leaves of Iris diaphragms it is not of very much use trying to cover them up with paint or varnish. The movement of the leaves will cause this to flake off. The dark colour of these leaves is produced by a chemical process which attacks the metal surface.

In special circumstances a film of soap-like material, of which several proprietary brands are available, can be rubbed over the lens surfaces to prevent misting on the surfaces of the lens by water vapour condensing on them. This should only be regarded as an emergency measure. As a rule the definition is softened appreciably. The film should be cleared off with spirit immediately it has fulfilled its purpose, so that no risks will be run of a hard skin being formed on the polished surface. Where a lens has to be used regularly in circumstances that tend towards misting of the surface a cover should be fitted on the front of the lens carrying a heated cover-glass, of basically the same type as electrically heated car windscreens. Such a cover glass must be optically worked. None is advertised on the British market.

If a lens is taken apart and it is found that a clamp ring has been sealed in then it should on no account be disturbed. It has probably been sealed as the final stage of a centring process.

If a lens surface is chipped but the lens urgently needed then first-aid treatment can be carried out by painting the flaked surface with an opaque black paint.

If a lens is to be stored for any length of time it should be kept in a cool place with lens caps on.

If a lens with a pair of glasses in it that are cemented together is to be used with a projector or enlarger (in the case of an enlarger only a condenser enlarger is considered here) care should be taken that the image of the light source

does not fall near this cemented pair. The Canada Balsam ages and goes yellow under the influence of prolonged heating in these circumstances, and to remedy this the glasses have to be recemented by the makers.

If it happens that a *glass becomes loose* in a cell of its mount in which it is held by a narrow bezel of metal which has been turned over the rim of the glass, it should be returned to the makers for repair. If excessive pressure is exerted in turning down a bezel the glass may become strained, and the definition of the lens impaired.

It goes without saying that a lens should be treated as a scientific instrument and not subjected to undue shocks or strains, or to any treatment that may damage either the glasses or the metal-work of the mount. As has already been pointed out above, the centring of a lens calls for exceedingly exact work, and a bruised thread or slightly buckled lens barrel means that the alignment of the parts may be upset. One concrete example, of the type of maladjustment that may be found, is in the case of R-R lenses or Petzval lenses for projection, where a crossed thread on the cell holding either set of glasses quite often leads to poor results.

If a lens is taken apart for any reason it is important to see that screw threads are clean before it is re-assembled and that the cells seat down properly. Otherwise the centring may be upset and the definition of the lens spoilt.

In some lenses the cells are made of different diameters so that it is impossible to reassemble them in the wrong order. This, however, is not the universal practice, and if a lens is to be taken apart for any reason it is advisable to make an identification mark on each cell. With some designs of lenses it is not possible to remove the central element in its cell for cleaning as it is glazed directly into the mount. It sometimes happens with this style of mounting that the iris diaphragm is close to the lens: in this event it is of importance to exercise great care not to buckle the iris, as the repair will probably mean the insertion of a new iris altogether.

AIDS TO BETTER PERFORMANCE

The Nature of Light

Up to a very few years ago all that the photographer needed to know about light was that it was something that travelled in straight lines, along the so-called rays of light, that white light could be split up by a prism into various colours, ranging from violet to red, and some simple consequences of these facts.

But the situation has changed considerably since then. And two main facts are responsible for this change. One is the introduction of screens such as *Polaroid* or *Pola* screens, which provide a cheap and simple way of dealing with polarised light. The other is the introduction of surface treatment of lenses. Both are recent developments. To understand them means having a rather more complete idea of the nature of light than hitherto.

There have been many theories about the nature of light, from the Arabs' idea that light was something sent out by the human eye to strike the object looked at, from Newton's idea that light consisted of particles with their "fits" of easy reflection and refraction, to modern quantum theories. The fact remains that there is still no satisfactory theory that covers the whole range of phenomena in which light is concerned. But while that may upset the theoretical physicist, it is of no great importance to the photographer. A sufficiently accurate account of the nature of light can be given to cover all the phenomena encountered in photography.

The main thing to be remembered is that light and radio waves are essentially the same. They each consist of an electric and magnetic disturbance travelling out from a transmitter, in one case a radio station, in the other an atom or molecule.

Whenever a ray of light passes through a point there are electric and magnetic forces introduced, that are absent when

the ray does not pass through that point. There is a simplification that can be made. Once the direction of the light ray and the exact electric force are specified the magnetic force can be fixed definitely by a mathematical calculation. For instance, in the simplest case the magnetic force is at right angles to the electric force and of a definite size. Because of this explicit mention of the magnetic force can be omitted. Any discussion of the electric force implies the corresponding behaviour of the magnetic force.

The electric force at any point *P* can be specified by drawing a line from the point, call it *PX* as shown on p. 271. The length of *PX* measures the strength of the electric force on some suitable scale, and the direction in which *PX* is pointing gives the direction of the electric force, the direction in which it would push an electrified particle.

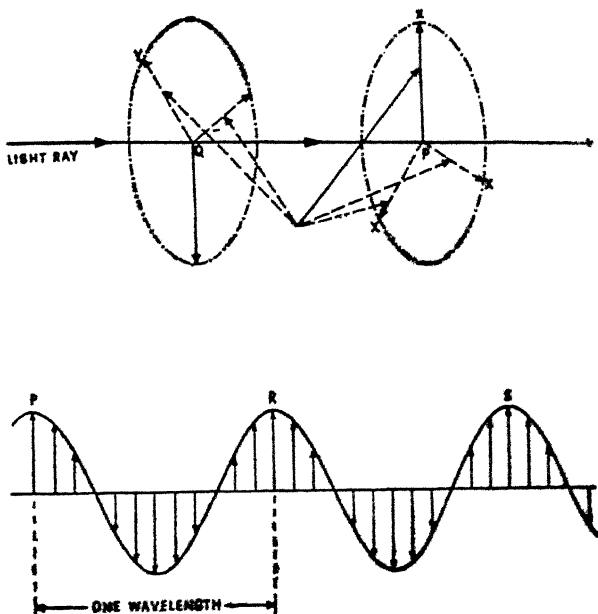
One thing can be said at once. The line *PX* is always at right angles to the direction of the light ray, as shown on p. 271.

The Transmission of Light

Concentrate attention on a point *P* on a particular light ray. Due to the light passing through *P*, as time goes by the electric force introduced at *P* goes through a cycle of changes. At a point *Q* on the same ray nearer to the light source the electric force goes through the same cycle of changes, passing through each stage at a time earlier—by a fixed amount—than the time at which the same stage is reached at *P*. This time difference between *P* and *Q* is the time taken for the electric disturbance to travel from *Q* to *P*.

The distance between *P* and *Q* divided by the time that the disturbance takes to travel from *Q* to *P* is the velocity of light, approximately 186,000 miles per second.

Now suppose that light of a pure colour is travelling along a ray. Being pure means that it is not split up into a spectrum when it passes through a prism. Concentrate attention on this ray at a particular instant. At every point on the ray a line can be drawn to represent the electric force at that



Top : The characteristic feature of light is that electric forces are introduced at points through which the ray goes. These electric forces are handed on from point to point along the light rays, so that they undergo a cycle of changes at each point on the ray successively. The cycle of electric force changes is the same at each point on the ray, but since it takes a finite time to hand on the electric force from point to point there is a time lag in carrying out the cycle (p. 270).

Bottom : At any instant there is a repeated pattern of electric force along a light ray. The length of the pattern is the wavelength of the light (p. 272).

THE PROPAGATION OF LIGHT

Instant, as shown on p. 271. Consider a point P on the ray and points to the right of it in the diagram, further away from the light source. The electric forces at these points are at different stages of their cycles of changes, and in fact lag behind that at P . The greater the distance from P the greater the time lag.

A stage is finally reached at the point R where the time lag is just equal to the time taken to go through the cycle of changes. The electric force at R is then equal to that at P . Beyond R the pattern that lies in the range P to R is repeated in the range RS , as shown, and beyond this all along the ray. The distance from P to R is the *wavelength* of the light.

As a rough guide the blue end of the spectrum can be taken to be light with a wavelength of 4,000 Ångstrom units, and the red end light with a wavelength of 8,000 Ångstrom units. One Ångstrom unit is one ten-millionth of a millimetre. Beyond these limits in the shorter wavelengths lie the ultra-violet radiations, and in the longer wavelengths the infra-red radiations, both of which can be used for photography under special conditions.

The colour of pure light depends only on its wavelength in air. When it is passing through glass its wavelength is changed somewhat, but returns to its original value as soon as the light emerges from the glass, and it is this wavelength in air that settles the colour. Composite light, such as white light can be split up by a prism into rays of pure light.

Polarisation

The exact path traced out with the passing of time by the point X , at the end of the line PX describing the electric force at the point P on the ray, defines the *polarisation* of the light.

If X describes a straight line through the point P the light is "plane-polarised."

If X describes a circle or ellipse with centre at P it is *circularly or elliptically polarised*.

The light from ordinary sources consists of light with all these types of polarisation mixed up.

The broad statement that we can then make as far as photography is concerned is this : the rays of light that reach the camera are in general neither of pure light, they can be split up by a prism into rays of all colours of the rainbow, nor have they a standardised polarisation. Rays from different parts of the subject will contain varying proportions of the colours of the spectrum in their make-up, and also will contain varying proportions of light of different types of polarisation.

By using filters to deal with light of different colours and types of polarisation marked improvements can be made in the quality of the negative.

Filters and Infra-Red Photography

As far as the use of filters, such as green or yellow filters, is concerned the only point of optical, rather than artistic, interest is that if some part of the subject contains too large a percentage of blue so that it would record too violently on the plate, the amount of blue in the rays coming from this region and reaching the plate can be cut down by using a yellow filter, or a green filter, and so on.

Of greater optical interest is the use of filters passing only infra-red light, and the precautions to be taken in using a lens with infra-red sensitive material.

The uses of infra-red rays in photography fall into two main classes, namely to bring out contrast which is not visible to the naked eye with light in the visual range, as in the decipherment of charred documents and so on, and to penetrate haze and mist.

The colour of an object depends on two things, the light striking it, and the pigment of its surface layers. The behaviour of two pigments may very well be entirely different when infra-red or ultra-violet rays are concerned from their behaviour with light in the visible spectrum. The pigment molecules of the two types react differently to different

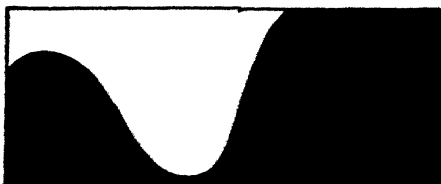
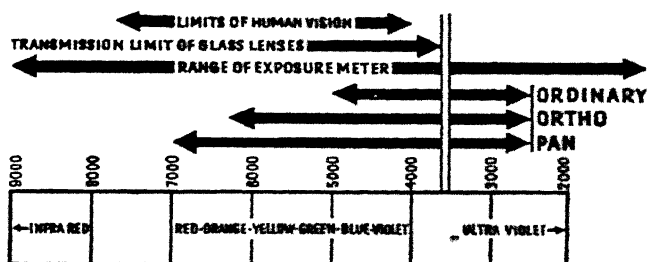
wavelengths of light. Contrast that is inappreciable when visible light is used may be brought out very well with Infra-red light, using a plate sensitive to this light.

The other application of infra-red light depends on the fact that it is scattered much less by the fine particles that make up a thin mist, or the smoke pall over a town. The scattering of light is a more complex process than reflection or refraction of light, and depends on the wavelength of light. A rule worked out by *Rayleigh* states that blue light of wavelength 4000 Ångstrom units is scattered sixteen times as much as red light of 8000 Ångstrom units, and infra-red light is scattered even less than red light.

When there is haze in the air the rays of light from a distant object are badly scattered before they reach the camera, the blue rays especially suffering this scattering. The outlines of the object are softened and may even dissolve in the mist. The red and infra-red are much less scattered and if all other light is filtered out a clear image in infra-red light can be formed on the plate. The haze-penetrating properties of Infra-red rays are of great value and importance.

Lenses for Infra-Red Use

To get the best results a lens specially corrected for infra-red light should be used. By the time that the wavelength of light used reaches the regions of the infra-red the secondary chromatic spectrum in normal lenses is distinctly noticeable in its effects. It results in the rays of infra-red coming to a focus at a greater distance from the lens than the visible rays of light, and this must be allowed for. *As a rule the separation between the visible and infra-red foci is about 1/250 of the focal length of the lens, say .015 inch for a 4 inch focus lens, but the exact amount depends on the lens used.* With a normal photographic lens there is also the possibility that the correction of the aberrations may not be maintained with infra-red light, but this as a rule is a matter of much less concern than the difference between visual and infra-red foci.



The aim of a filter is to pass only a certain coloured fraction of the light incident on it, including in the term *light* both ultra-violet and infra-red radiation. The absorption curves of three different filters under the spectrum show this effect; the white regions indicate the extent of light passed by the filter—the black regions denote parts of the spectrum blocked out by it. Over the spectrum the "coverage" of the three basic types of sensitive material is roughly indicated and also other factors that complicate exact reproduction of the spectrum in full (p. 273).

THE WORK OF FILTERS

Some miniature lenses are now fitted with focusing scales calibrated for infra-red work, so that infra-red photographs can be taken in a straightforward manner.

Calibration for Infra-Red

It is advisable and easy to calibrate a lens for use with infra-red light, and preferably the calibration should be carried out with the infra-red filter that it is proposed to use, as these differ among themselves quite considerably as regards the part of the spectrum they transmit and this difference is not emphasised by any visible difference.

The method of testing a lens for axial chromatic aberration has been described in the previous chapter. It can be applied to calibrating a lens for infra-red work.

Set up a chart, at a distance of 100 inches from the lens say, and focus the camera on this visually, using a ground glass focusing screen. Arrange charts further away so that their images in visible light have separations from one another of about .001 inch for a 1 inch lens, .004 inch for a 4 inch lens and so on, with about six or seven charts in use altogether. The separations of the charts to give these distances between the corresponding images can be found sufficiently closely from the formula

$$\text{Chart separation} = \text{image separation} \times D^2/f^2,$$

where D is the distance of the first chart, and f is the focal length of the lens.

With $D = 100$ inches and $f = 4$ inches, and an image separation of .004 inch as mentioned above, the formula gives

$$\begin{aligned}\text{Chart separation} &= .004 \text{ ins.} \times 100^2/4^2 = .004 \text{ ins.} \times 25^2 \\ &= .004 \text{ ins.} \times 625 = 2.5 \text{ ins.}\end{aligned}$$

By judging the quality of the charts, as they are reproduced with this setting of the camera and with an infra-red filter, it is possible to estimate to the nearest .004 inch which is the chart in sharpest focus, and so to obtain the distance between the visual and infra-red foci sufficiently accurately.

Suppose that it is .016 inch. The next thing to do is to use this fact to relate visible and infra-red focusing scales.

If the camera is focused on an object at a distance V in front of the lens with visible light, and if the separation, as just measured, is l inches between the visible and infra-red foci, then the distance of an object that is in sharp focus with infra-red rays is given by the formula, with sufficient accuracy for ordinary purposes.

$$\text{Distance of object focused in infra-red} = V + l \times \frac{V^2}{f^2}$$

For example if $l = .016$ inch, $f = 4$ inches, and D is 15 feet, i.e., 180 inches, then the distance focused in the infra-red is

$$180 \text{ inches} + .016 \text{ inch} \times \frac{180^2}{4^2} = 180 \text{ inches} + 32.4 \text{ inches, i.e.,}$$

17 feet 8½ inches to the nearest half-inch.

In this way a chart can be drawn up relating visible and infra-red

focusing distances ; the only distance that cannot be handled in this way is the infinity setting of the camera. When an object at infinity is in sharp focus with infra-red light the distance of the object that is in sharp focus with visible light is given by the formula.

Visual focus = $f^2 \div l$ where f and l have the meanings already explained. Thus if $l = .016$ inch and $f = 4$ inches, the visual focus is at $4^2 \div .016 = 1000$ inches, or 80 feet sufficiently accurately. In quite a lot of work there is no appreciable difference between 80 feet and infinity, and the visual and infra-red foci can be taken as identical. But for the best results the difference should be taken into account.

The calibration just described is effective down to distances of ten to fifteen times the focal length of the lens, i.e., down to about 4 or 5 feet for a 4 inch lens. For close-up work the lens should be re-calibrated in exactly the same way for the new conditions of use.

Even if the true infra-red type of work is replaced by an approximate type, using panchromatic material with a red filter the same precautions about calibration are often worth while.

Polarising Filters

The main use of ordinary or infra-red filters is to obtain a better tonal reproduction on the negative, or to enhance the contrast of the image in a desired way. The main use of polarising filters is to cut out the unwanted glare from some polished surfaces, or the reflections from the surface of a liquid, so that sub-surface detail can be photographed. The types of surface that can be dealt with are those which are sufficiently even to reflect the light rather than scatter it. Glittering surfaces such as those of rough silver foil cannot be dealt with in the same way by using polarising filters. Although such surfaces reflect light rather than scatter it, the reflection takes place at so many differently arranged facets that the light is effectively depolarised.

Polarising filters deal only with plane polarised light. As explained earlier in this chapter, this means that the end-point X of the line PX representing the electric force moves in a straight line through the point P . This is shown on p. 279, which shows the two independent directions at right angles to one another along which X can move. The ends of the arrow heads show the limits of movement of the point X . The light can be either polarised so that X moves as shown in the first diagram, or polarised so that X moves as shown in the second diagram.

If it is polarised so that X moves in the direction shown on p. 279, in the bottom 4 diagrams then it can be considered as being made up of light polarised in each of the ways illustrated, call them for short the up-and-down and cross-ways directions of polarisation. Light polarised in a direction that is neither up-and-down nor across but is slanting as shown can be taken as being partly light polarised in an up-and-down direction, and partly of light polarised in a cross-ways direction. The same holds for more complicated movements of X .

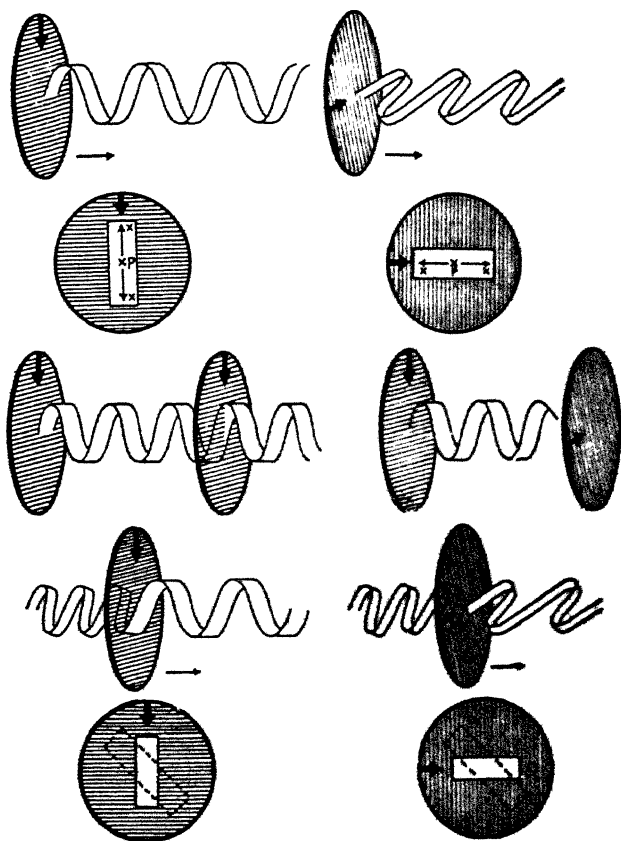
A polarising filter allows only light polarised in a certain direction, suppose for instance that it is the up-and-down direction, to pass through. This direction is marked on the front of the filter mount.

When light polarised in a direction that slants away from the up-and-down direction encounters the filter, this latter cuts out that part of the light that can be considered as polarised in a cross-ways direction, and allows to pass only the part that is polarised in an up-and-down direction. The light coming through a polarising filter is polarised in a specified direction only.

Light obtained from normal sources contains rays polarised in every direction. The filter cuts out all but that polarised in the direction marked on the filter mount.

When light from one filter with its polarising direction in an up-and-down direction falls on another filter also with its polarising direction up-and-down the light passes on unchanged. The filters are then *parallel*. When it falls on a filter with its polarising direction cross-ways on, no light gets through. The filters are then *crossed*. With the second filter in a position between its parallel and crossed positions part of the light only is passed by it.

When light is reflected or refracted by a mirror or lens its polarisation is unchanged in direction, although the light itself may be cut down in intensity. This is brought out on p. 285. The ray of light marked AB is polarised in the plane of the paper. The point X at the end of PX , described above, always lies in the plane of the paper before reflection.



Top : The light passed by a polarising filter has the direction of the electric forces fixed in direction, and related to the orientation of the filter. The direction of the electric force is indicated by *PX* as shown lower.

Middle : When the two filters are parallel the light transmitted by the first is passed by the second. When they are crossed the second completely cuts off the light (p. 277).

Bottom : Part only of light polarised at an angle to the polarisation direction of the filter is transmitted (p. 278).

POLARISING FILTERS

Then after reflection (or refraction) at the surface shown it is still polarised in the plane of the paper, although the reflection may have cut it down in intensity considerably. The end-point *X* still moves in the plane of the paper, without any tendency to move out into space and move in and out of the paper.

In the same way if the point *X* moves only in and out of the paper before reflection or refraction, then it moves in the same way after reflection, without any tendency to move in the plane of the paper.

These remarks hold only for reflections at polished surfaces, which reflect light like a mirror, such as a liquid surface or that of plate glass. *When light is reflected or scattered by a rough or matt surface the direction of polarisation is changed in an arbitrary manner.* If the light falling on a polished surface has been passed through a polarising filter, then it retains its polarisation after reflection and can be cut off by a second filter. The same light falling on a rough or matt surface has its polarisation changed in a random way by every element of the surface, and can no longer be cut off by a second filter.

Light is only polarised when reflected from a transparent surface (glass, varnished and glazed surfaces, water, etc.), but not from opaque surfaces (polished metal surfaces, etc.). Such light cannot therefore be suppressed by a polarising filter.

This property of light finds an immediate application in the photography of things such as framed oil paintings and the like, or polished objects whose surface details are to be photographed, provided that these surfaces are sufficiently even to reflect light rather than scatter it. As a rule the reflections at the glass or polished surfaces are particularly troublesome and frequently ruin the picture altogether.

To cut out such reflections the first step is to illuminate the objects with polarised light. This is done simply by putting polarising filters over the lamps used. These filters can be made of a lower quality than the filters used over the photographic lenses, and at a lower price, and it should not be expected that one of them can be used as a filter on a lens and provide good definition. Another thing is that care

should be taken not to overheat the filter. A temperature above 75°C for any length of time is harmful to the filter. The lamps may have to be run at a reduced voltage, except for the actual exposure, in order to keep the filters cool.

To the naked eye there will still be troublesome reflections. But if a polarising filter is held in front of the eye and slowly turned round a position will be reached when they are cut out. Note the position of the index mark on the filter when this happens. Put the filter on the lens with the index in the same position to get the photograph. Alternatively the same procedure can be followed with the image given by the lens on a focusing screen in the camera.

This technique is particularly valuable in the type of table top or still life photography where objects are mounted on sheets of glass. It cuts out the reflections from the glass under difficult lighting conditions.

There is one thing to notice with this technique. Diffusing screens in the lamps must be put between the bulbs and the polarising screens. Placed after the polarising screens they depolarise the light and bring the whole method to naught.

Polarising screens can also be used without artificial means of illumination. Their value in this case depends on the fact that light reflected from a polished surface is partially or completely polarised, depending on the angle at which it strikes the surface.

The light that is reflected at such a surface, and which may give distinctly troublesome reflected images that are reproduced on the plate, is completely or partially polarised. If it is completely polarised it can be cut off by a polarising filter and the reflected images eliminated from the negative. If it is partially polarised, that is to say if it consists of rays which have a strongly pronounced tendency to be polarised in a certain direction, it can be greatly reduced in intensity by using a polarising filter. Objects behind, or even in, such a reflecting surface send light to the lens that is not polarised in any specified direction and is not cut off by a polarising filter.

With a properly adjusted polarising filter the detailed

structure behind the polished surface is not hidden by the reflections seen without the filter. The angle at which to put the filter on the lens can be found by turning the filter in front of the eye as explained above.

Polarising filters are of comparatively recent introduction, but are coming into wider use. As explained above, the technique of their use is simple, and their value especially under difficult lighting conditions is self-evident.

Scatter in the Lens

There are several factors which operate to impair the contrast on a photographic plate, such as scatter in the emulsion and so on. And one of the most important of these is the scatter of light within the lens.

When a ray of light strikes a glass to air surface, either from the outside or from inside the glass, a part of it goes through in the normal and anticipated way, but a much smaller part is reflected. The exact amount reflected depends on the angle at which the ray hits the surface, but an approximate value for the intensity of the reflected light is 5% of that of the incident ray.

If a part of the light is reflected at a surface that it should cross then it is thrown back towards the front of the lens. A second reflection sends it back in the proper direction, towards the plate. But since it has deviated from the orthodox path it cannot be expected to hit the plate at the proper point, the point where the unreflected ray cuts the plate. The rays that come from any object point in front of the lens, and that undergo reflections at the same pair of glass to air surfaces come together in an image point, which may be at a considerable distance from the plate or quite near to it.

If the image given by the reflected rays is near the plate it gives rather a bright light patch or "ghost image." If it is at a considerable distance from the plate it merely produces a diffuse illumination over all the plate area. By raising the general level of illumination, and so adding to any fog that may already exist on the plate it impairs contrast,

especially in the regions where the tones of the picture are most subdued. Ghost images of course are distinctly unsightly by themselves.

Diffuse illumination or ghost images as just described arise from every pair of glass to air surfaces in the lens and from every point of light that can send rays to the lens. The two logical ways to cut down the effects of these are obvious : to cut down the number of glass to air surfaces in the lens and to cut out all unnecessary light that can reach the lens.

Lens Hoods

The first is a matter for the lens designer. It is difficult enough to get a really good performance out of a lens without having to worry unduly about the number of glass to air surfaces in the lens, but it always has to be borne in mind that they must be kept as few as possible.

The second is a matter for the actual user of the lens. *It simply means that a lens hood should be used so that only light from the actual required scene reaches the lens. It is impossible to ensure this completely. Some unwanted light will reach the lens, but the longer the lens hood the smaller the amount of this light. The important thing to notice, however, is the size of the lens hood, as far as front diameter is concerned, must be chosen so that no vignetting is introduced by it. All the rays of light, from an object point required in the picture, that reach the lens without the hood must reach it with the hood in place.*

It is a simple thing to work out the proper size of the front of the hood to give this. The greatest efficiency is obtained when there is a mask at the front of the hood of nearly the same shape as the plate or film area being used. The exact shape and size are calculated in this way :

Suppose that the mask is m times the focal length of the lens, then :

Long side of mask = $m \times$ long side of film + diameter of front glass of lens.

Short side of mask = $m \times$ short side of film + diameter of front glass of lens.

Thus if the lens is of focal length 2 inches, and the mask is 3 inches long, then $m = 1\frac{1}{2}$. If the film is 35 mm. film as used in miniature cameras, i.e., 24×36 mm, or sufficiently closely $1 \times 1\frac{1}{2}$ inches, and the lens has an aperture of $f\ 2$, i.e., the diameter of the front glass is 1 inch, then

Long side of mask = $1\frac{1}{2} \times 1\frac{1}{2} + 1 = 3\frac{1}{4}$ inches.

Short side of mask = $1\frac{1}{2} \times 1 + 1 = 2\frac{1}{2}$ inches.

If the mask has a circular opening then

Diameter of mask = $m \times$ diagonal of film + diameter of front glass of lens.

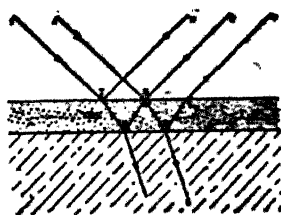
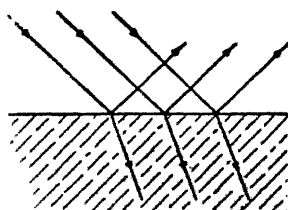
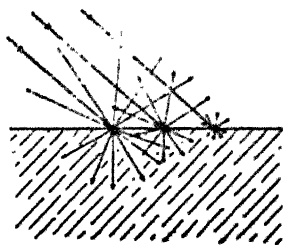
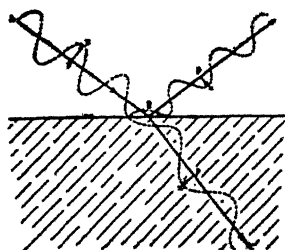
The use of a lens hood helps considerably in improving the contrast.

Surface Films

One factor that could not be deliberately controlled until a few years ago was the amount of light reflected at the glass to air surfaces. In the cases of some older lenses which had acquired a *bloom* on their surfaces with the passing of time the amount of reflection was cut down at each of these surfaces. But this blooming could not be produced regularly as a practical proposition. It can be counted as one of the most significant advances of recent years that processes have been found by which the surface reflections can largely be eliminated. It is too early as yet to say that the processes have been perfected, but they have been developed to such a stage that they are definitely a practical proposition for the average photographer. The films produced are sufficiently durable to stand up to reasonable conditions of camera use.

How Light is Reflected : To understand how the films applied in this treatment cut out the reflections it is best to consider in detail how light is reflected and refracted.

When rays of light strike a surface separating glass and air every point on the surface is stimulated to send out rays of light, as shown on p. 285. The arrow heads show how far the stimulated rays have travelled at a particular instant. Because the rays of light hitting the surface make an angle with it the same state of stimulation is given to points on the surface at different times, and the rays that are sent out in consequence are retarded by corresponding amounts.



Top left : The polarisation of light, i.e., the way in which the electric forces it induces vary, is unchanged when light is regularly reflected or refracted as at the surface of a lens or at a mirror. The end-point of the line describing the electric force continues to move either in or perpendicular to the plane of the paper after refraction or reflection. This does not hold when the light is scattered (p. 278).

Top right : Rays of light that strike a surface stimulate each point to send out rays in all directions, both back into the air or initial medium whatever it may be, and into the body of the material or into the air. This holds whether light is incident on a surface separating glass and air or separating two media, from either side (p. 286).

Bottom left : When the surface separating glass and air or two media is regular and smooth there are definite relations between the rays sent out under stimulation. Most of them cancel one another out because of interference, and only a small group survive, the reflected and refracted rays.

Bottom right : When a film is put on glass there are reflections at the air-film and film-glass interfaces. By suitable adjustment of the strengths of these reflections and the thickness of the film these can be made to interfere with one another, and there is no resultant reflection. This is the basis of Surface Treatment (p. 286).

THE REFLECTION AND REFRACTION OF LIGHT

All these stimulated rays "Interfere" with one another. At any point in space the electric force due to some rays will be in a certain direction, and the electric force due to the remainder of the rays will be of the same size but in the opposite direction. The two forces cancel out and there is no resultant electric force. Or, what is the same thing, there is no ray of light going through the point. This happens at the vast majority of points. In only a finite number of directions are there electric forces which do not cancel. These are the reflected rays. The same kind of thing happens with the rays that cross the surface and are refracted. Page 285 shows the only rays that survive when the interference of light is taken into account.

Primitive Surface Treatment : Although this phenomenon has been described for a glass to air surface the same thing happens at every surface separating two media with different indices of refraction. Some light is reflected at the surface, but the greater part crosses the surface and is refracted. The amount of light reflected depends to some extent on the angle between the rays and the surface, but it does not change very rapidly for moderate angles of incidence. It depends also on the ratio of the refractive indices of the two media.

For perpendicular incidence the amount reflected at each surface is $\left(\frac{1-x}{1+x}\right)^2$ where x is the ratio of refractive indices across the surface, i.e., where $x = 1.69$ it is $\left(\frac{.69}{2.69}\right)^2 = .065$.

If we have surfaces separating media such that the ratio of refractive indices across each surface is the same the percentage of light reflected at each surface is the same.

Suppose then that we have glass with a refractive index of 1.69, corresponding to Double Extra Dense flint glass. With light falling on this at right angles the percentage reflected is 6.5%.

Now suppose that a film of some substance with a refractive index of 1.3 is coated on to the glass as shown on p. 285

The ratio of indices across the air to film surface is $1.3 \div 1 = 1.3$, and across the film to glass surface $1.69 \div 1.3 = 1.3$. Hence the same amount of light is reflected at each surface, in this case 1.7%. The total reflection at the two surfaces is then 3.4%, i.e., the reflection has been almost halved. The reduction is a maximum when the Index of the film is the square root of the index of the glass, as in the case just quoted. The reduction takes effect at both the surfaces where the light enters and leaves the glass.

This is the crudest form of surface treatment. It does not depend on the thickness of the film and reduces the reflected light to about 50% of its previous value.

Controlled Surface Treatment : Better and more valuable results are obtained by controlling the film thickness carefully. The reflection can be reduced from 6.5% to less than 1%. This more exact and precise use of a surface film depends for its success on the Interference of light.

The ray AB hits the upper surface as shown on p. 285. Part is reflected along BC, and part refracted along BD to the lower surface. At D some is reflected along DE and into the air again along EF, and the greater part is refracted along DG into the glass. The same thing happens to the ray ST.

The ray VX comes to the point B, which coincides with the point X, and so out into the air along the path BC.

Now by choosing the Index of the film properly, i.e., making it equal to the square root of the Index of the glass, the Intensity of the light or electric force propagated along BC from the ray AB is the same as that derived from ST.

The ray that comes to B by the path ST - VX has a longer distance to travel than the ray AB, and takes longer to get there. As a result the electric force that it produces at B is at a different stage in its cycle of changes to that caused at B by the light reflected from the ray AB. By choosing the path difference between the rays suitably the electric forces can be made to be out of step by half a cycle. The electric force due to VX is then equal to that due to BC, but points in the opposite direction the two forces cancel out and as a result there is no reflected ray.

The light that should be reflected from AB and the light that should cross the surface from VX having cancelled one another out their energy must find other channels, and in fact it goes to augment the amount of light passed by the lens. Cutting down the reflection automatically increases the amount of light crossing the surface.

Results of Surface Treatment. Surface treatment improves the performance of a lens by increasing the *transmission* of the lens, and by increasing the contrast of the image.

The transmission of a lens indicates the percentage of the light incident on the lens that goes to form a useful image. It may be defined thus: of the light radiated by an object point P , 100 units (on some suitable scale) could get through to the image point P^1 if only the geometry of the ray paths were taken into account and if there were no light losses in the lens. Because of losses by absorption in the glass and reflections at the air-glass surfaces only N units reach the image point P^1 . The transmission of the lens is then $N\%$. The transmission varies somewhat with varying positions of P in the field of the lens. As a rule it is given only for the case where P is at infinity on the axis of the lens.

With an $f/2$ lens of the *Speed-Panchro* type having untreated surfaces the transmission is in the neighbourhood of 55–60%. For the same lens with all its surfaces treated the transmission is 85–90%. Even for a simple *Cooke Triplet* the transmission for an untreated lens is about 65–70%, whereas for the same lens with all its surfaces treated the transmission is about 90–95%, and for a lens with only the inner surfaces treated the transmission is 80–85%.

These transmission differences between lenses with and without surface coating have led to calibration systems based on actual lens transmission.

An example is the *T-stop* system. If the light passed through a particular lens working at fN' is the same as that passed by a lens of the same focal length and 100 per cent transmission working at fN then the *T-stop* number of the lens is N . Note that N' is always greater than the standard f number N . The exact relation between the *T-stop* number N' and the f number N depends on the presence or absence of non-reflecting films and their efficiency and the absorption of light within the glass of the components. We can, however, take these approximate

values for the ratio of T-stop to f number.

| | | | | | | |
|------------------------------|------|------|------|------|------|------|
| Number of air-glass surfaces | 2 | 4 | 6 | 8 | 10 | 12 |
| N'/N for uncoated surfaces | 1.06 | 1.12 | 1.18 | 1.24 | 1.30 | 1.36 |
| N'/N for coated surfaces | 1.02 | 1.04 | 1.06 | 1.08 | 1.10 | 1.12 |

Thus for an $f3.5$ Cooke triplet at full aperture without coated surfaces, the T-stop number is $3.5 \times 1.18 = 4.13$ or about 4.1.

The introduction of T-stop numbers is an important step forward, but it does not provide a complete statement of the light-gathering power of the lens. It deals only with the near central region of the lens. Towards the edge of the field vignetting becomes of importance. At full aperture the relative edge to centre illumination may lie in the region of 40–60 per cent and varies from lens to lens, as well as varying at different apertures in the same lens as the iris is closed. The next step, and an important step, forward is to give a vignetting factor or series of vignetting factors for each lens.

The contrast of the image is discussed in detail in works concerned with the processing of the negative material (e.g., *Developing*, by C. I. Jacobson. Focal Press). It is concerned with the ratios of the amount of light falling on different regions of the negative and their effects on the final image. Cutting down the reflection of light at air-glass surfaces by the use of surface treatment means that less unwanted light from the highlights of the scene finds its way into the images of the shadows, with a consequent improvement of contrast in these. Gradations of detail in the shadows may then be reproduced, that would be swamped by stray light from the highlights in the absence of surface treatment or blooming.

While the gain in transmission is very useful on many occasions, experience over the past few years has shown that the gain in contrast and rendering of shadow detail may be of much greater importance.

Production of Films. The actual coating of the lens surfaces has been reduced to a fairly straightforward job.

Historically the earliest method was to use a chemical agent to attack the surface of the lens and dissolve out part of the glass, so that there remained a thin film of silica of the proper thickness. This method is not widely used at the present time. Another method in which an organic film of a soap-like material was deposited is now of academic interest only.

Films today are practically all formed by evaporating a fluoride, such

as lithium fluoride or magnesium fluoride, on to the lens in a high vacuum. The thickness is controlled by adjusting the time of evaporation. There are two classes of fluoride film produced in this way. The first is moderately hard and results from a straightforward evaporation in a high vacuum. The second is produced by the same process together with a baking or pre-heating treatment. The second class of films are much harder than the first, and are in fact about as hard as the glass itself on which they are formed. They are usually described as *hard films*.

No matter what film-forming process is used the thickness of the film to give the proper result depends on two things. The first is the wavelength or colour of the light. The second is the angle at which it meets the surface. No method has been devised of eliminating the dependence of the film thickness on these two factors, and a compromise has to be reached. The thickness is usually chosen for light meeting the surface at perpendicular incidence, and is then equal to a quarter of the wavelength of the light used. The wavelength of the light for which the reflection is eliminated depends upon the purpose of the lens, but is usually in the green region of the spectrum. It means that the film is about eight to ten millionths of an inch thick.

There is a residual of reflected light from regions of the spectrum on both sides of the wavelength for which elimination is complete, and this residual gives the surface-treated lens its characteristic colour. For average photographic use the surface of a treated lens is a deep blue or purple-blue. For a lens intended for infra-red the surface is a pale whitish-blue.

Surface-treated lenses both for photography and projection purposes are being produced now by all the leading makers. In some cases the blooming on the inner surfaces is moderately hard, and the outer surfaces either left untreated or given hard films. In other cases all the surfaces, inner as well as outer, have hard films. Facilities are also available for treating lenses produced before these processes were developed.

Mention should be made at this point of *interference filters*. There are filters with narrow transmission bands which depend for their functioning on the same interference phenomena as are responsible for reflection reducing coatings. In this case, however, a series of thin layers of different material are deposited in place of a single layer, and the filtering action is produced by the interference of light reflected at the various surfaces separating these media.

ACCESSORIES

View Finders

The easiest and most obvious way of finding out exactly what picture the lens is throwing on the plate is to put a ground-glass screen in its place and then to examine the image thrown on this. The etched surface of the glass has to occupy the same position as the emulsion on the plate. Rather more devious ways of arriving at the same results, or nearly the same results, are to use *view-finders* and *range-finders*.

Focusing Screens: As far as getting the position of exact focus is concerned when using a focusing screen, two points should be borne in mind. The first is to use a magnifier with a reasonably high power, about 8x to 15x is most suitable. The second is to be certain that the magnifier is focused exactly on the ground surface of the glass. This can be done fairly easily by drawing fine pencil lines on the ground surface, by focusing carefully on these, and by noticing that both the image and the pencilled lines are in sharp focus together when examined with the magnifier. The screen of course is used with its ground surface towards the lens.

This focusing serves for most cases. Where a really critical setting is needed a clear glass screen should be used with fine rulings engraved on it or photographed on it. The magnifier is focused on these rulings, and the image given by the lens is brought into sharp focus at the same time. The final setting is done by focusing the lens, with a fine movement, to eliminate all parallax between the image and the lines. This simply means that when the eye is moved slightly there is no relative movement of the lines and the image as seen through the magnifier. A very exact setting can be made in this way.

A glass screen suitable for this work can be made readily by photographing lines, drawn in Indian ink and about .02 inch wide, and drawn on a matt white surface such

as cartridge paper, on a slow process plate at a reduction of about twenty to one. The lens used should be stopped down to one or two stops below its maximum aperture to get the best definition.

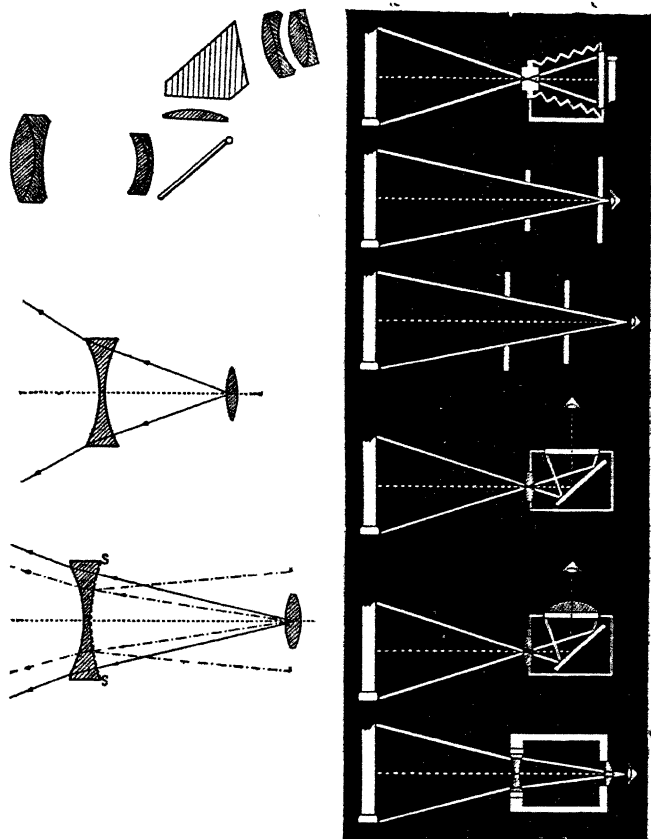
While the clear glass screen and parallax focusing are more accurate, the ground glass screen is more useful in composing the picture. A useful compromise is a ground glass screen with a clear centre.

A variant of the ground glass focusing screen has been described in a recent patent, which consists of a sheet of glass ground on both sides in squares like a chess board, with a ground square on one surface opposite a clear square on the other surface. The setting is to be made when the images on both surfaces of the glass are equally diffuse. With this type of screen a magnifier of 8x at the most is about the strongest that can focus both sets of ground squares at the same time. It is particularly adapted for use with lower power magnifiers, and especially as a screen in a reflex camera where the hood may prevent the use of a high power magnifier. The exact plane in sharp focus lies between the two surfaces. It cannot be assumed that it is midway between them. Because of spherical aberration the quality of the out-of-focus images on both sides of the plane of exact focus is different, and this means that the plane of sharpest focus is not necessarily midway between two positions where the definition is equally diffuse: it would be if there were no spherical aberration in the lens. As this type of screen is mainly of use in reflex cameras it is best calibrated in the way that the calibration of a reflex focusing screen is effected, as described below.

Another method of getting the position of sharp focus most easily is to put a mask in front of the lens consisting of a series of parallel slits about $\frac{1}{8}$ inch wide, or consisting of holes about $\frac{1}{8}$ inch square. It can be improvised easily from stiff card and an old filter holder. With this mask in place the out-of-focus light patch is split up into a number of separate patches, and this gives a more definitely diffuse appearance to the image on the screen. The image then seems to snap into focus more abruptly.

Checking Reflex Focusing: The first variant of this simple use of a focusing screen is to bend the light by a mirror and receive the image on a screen so that it is visible right up to the moment of making the exposure. This of course is just the basic feature of the single-lens reflex camera.

The main thing to be checked over with a reflex camera,



Right : The simplest way of looking at the scene is on a ground-glass focusing screen. After that a direct vision finder may be used (two versions shown). Slightly more complicated is the reflex finder, the brilliant view-finder, and an optical view-finder (pages 291-297).

Left : Various types of view-finders are shown in outline ; a Zeiss "Flektoskop," an optical finder, and an "Albada" finder (pages 294, 296, 297).

VIEW-FINDERS

either single or twin lens type, is whether the image is sharply in focus on the plate when it is in sharp focus on the screen. This can be done very easily, whether the screen is a straightforward ground-glass screen or of the more complicated type just described, by using the procedure described on page 239 to test for axial chromatic aberration, or used in calibrating a lens for use in the infra-red, as dealt with in the previous chapter. Objects are set up so that their images are separated by about .003 inch to .004 inch as there described. The central object is brought to a sharp focus and an exposure made. If the screen and plate are accurately matched the central image is perfectly sharp, with slightly diffuse images on either side. If a nearer object is in sharpest focus then the plate is further away from the lens than the focusing screen. The amount can be estimated as explained in the sections dealing with chromatic aberration and infra-red foci.

There is no basic difference between the single-lens and the twin-lens reflex cameras except that the twin-lens sees the picture from a slightly different viewpoint, a fact that is discussed below for view-finders in general. One rather definite psychological advantage of the twin-lens is the fact that the picture is in view all the time, and does not vanish as the exposure is made, but this is purely a matter of psychology and not of optics.

A variant of the simple reflex camera is the *Flektoskop* of Zeiss and similar reflex focusing devices such as the *Kilfit*, *Teweflex*, *Leitz Reflex Housing*, etc., for use with long focus lenses. The layout of this is shown on p. 293. Another variant is the type of view-finder used with some types of 16 mm. movie cameras, e.g., the *Goerz* reflex focuser, which consists of a reflex camera arrangement and built-in magnifier. It provides at one and the same time a method of getting the picture into critical sharp focus on the film, and of composing the picture exactly as it is to be recorded on the film, without any trouble due to parallax error as described below.

In using a focusing screen or a reflex arrangement of a type mentioned above the picture is composed and focused at the same time. Other devices deal with only one of these functions at a time, either focusing or composing the picture,

and so can be classed as either range-finders or view-finders. View-finders are dealt with first and then range-finders.

Direct Vision Finders: The simplest type of view-finder comprises a mask or frame mounted in front of a small viewing hole in a piece of metal. The distance between the sighting hole and the frame is normally equal to the focal length of the lens with which it is used. The frame is the same size as the plate covered. Then, apart from the slight *parallax* error described below, the picture seen framed by the wire frame or mask, with the eye at the sighting hole and the lens focused for infinity, is just the picture that the lens throws on the plate.

As a rule a lens is focused by varying its distance from the plate to take into account the varying distances of the objects to be photographed, although with some lenses, the focusing is done by varying the focus of the lens slightly (p. 167). When the focusing is carried out by moving the lens there is a definite advantage to be gained in mounting the frame or mask of the view-finder on the lens panel. As the lens moves away from the film or plate its rear nodal point also moves away from the plate, and as already explained on p. 34 the perspective frame is separated from the viewpoint by the same distance as the rear nodal point and the plate. If the wire frame or mask, which serves to mark off the area of the picture that will be recorded on the film, is fixed to the lens panel, then it automatically moves forward through the same distance as the rear nodal point of the lens. The distance of the sighting hole from the wire perspective frame is automatically kept the same as the distance of the rear nodal point of the lens from the plate or film. The picture then covered by the frame is just that which the lens will record on the film or plate.

If the lens is moved without any corresponding movement of the wire perspective frame the field recorded on the film is smaller than the field seen through the frame, except when the lens is focused on an object at infinity and so at its nearest approach to the plate. The amount of the discrepancy can be judged from the figures given below.

Suppose that a plate $2\frac{1}{2}$ inches by $2\frac{1}{2}$ inches is used in the camera with a $3\frac{1}{2}$ inch focus lens, and that the wire frame is correspondingly $2\frac{1}{2}$ inches by $2\frac{1}{2}$ inches and $3\frac{1}{2}$ inches away from the sighting hole. When the lens is focused on infinity the picture seen through the wire frame is just that which is thrown on the plate. When the lens is focused on an object at 2 feet 6 inches away from it the picture recorded is only about 90% of that seen through the frame.

Another form of direct-vision view-finder consists of two metal masks mounted one behind the other, so that when the rear mask opening just covers that of the front mask the rays of light that reach the eye are correctly limited when the lens is focused for infinity. When the lens is focused for infinity the picture seen through the two frames is just that recorded on the plate.

Optical Finders: The types described immediately above are simple and straightforward, and without optical elements in their make up. Equally common types of view-finder, employ inexpensive optical elements. Because of their simplicity no provision is made as a rule for the change in the field recorded as the lens is focused on close distances.

The simplest type consists of a moulded converging lens, a mirror, and a small ground-glass screen as shown on p. 293. The focal length of the lens and the size of the glass screen are matched so that the picture on the screen is, on a smaller scale, just the picture thrown on the plate when the lens is focused for infinity.

An improvement on this simple type consists in mounting a lens in contact with the ground glass screen so that rays of light are more concentrated near a point where the observer's eye will be placed, as shown on p. 293. This is the "brilliant" view-finder.

Another type consists of a telescope as shown on p. 293 where a diverging lens is followed by a converging lens. The field viewed by a finder of this type is governed by the distance apart of the two lenses and the size of the clear aperture of the diverging lens. These are matched so that the field viewed is that recorded on the plate when the lens is focused for infinity. The focal lengths of the two lenses are chosen so that distant objects can be viewed through the finder without eye-strain.

Albada Finder : A more complicated construction is adopted in the *Albada* type of finder used by Zeiss, in which a larger field is covered by the finder than that recorded on the plate. The part of the field seen that is recorded, is marked off by a white frame which seems to be superimposed on the scene to be photographed. This type of finder is of special use in sport photography. One particularly ingenious type used is shown on p. 293. The negative or diverging lens is lightly silvered on its inner surface, so that a white frame on the mount of the converging lens is reflected at this surface. The radius of the inner lightly silvered surface is chosen so that the image it gives of the frame can be comfortably viewed at the same time as a distant object.

This is the simplest type of *Albada* finder. There are others of more complicated construction that give an improved performance, but the basic principle remains the same, namely to cover more than the exact area to be recorded on the film or plate and to mark off this latter with an easily visible line.

Another type of finder uses two positive lenses, the first forming an image in the plane of a suitable mask, and the second serving as a magnifying lens to view the image. A prism system is inserted in such a finder to provide an erect image. Finders of this type are the *Leitz Vidom* (which gives an erect image reversed left to right) and the *Leitz Imarect* and the *Zeiss Contax Universal* finder. In the *Leitz* finders provision is made for using the finder with lenses of different focal lengths by varying the mask size by means of a knurled ring. In the *Zeiss* finder the same problem is handled by mounting a series of lenses on a turret and bringing the appropriate lens into place to form an image on the mask. In these constructions the ratio between the size of the mask and the focal length of the lens system in front of it is equal to the ratio between the size of the negative and the focal length of the camera lens.

Some view-finders now coming on to the market rely on a lens system having variable focal length or variable telescopic power instead of interchangeable lenses or variation of mask size. These are particularly useful when a large number of camera lenses of different focal length are likely to be required or when a variable focal length camera lens is being used. These viewfinders work on the same optical principles as the variable focal length lenses described on page 211 and their constructions are usually simplified versions of the diagrams on page 214.

Ultra Close-ups

When close-ups are being taken at very short ranges there are two problems to be faced, problems which are encountered in every case when a photograph is taken, but which are now of enhanced importance. These are to make sure that the scene is in sharp focus, for there is very little depth of field at these close ranges, and to make sure that the correct area of the field is seen by the camera, since parallax errors assume a much greater importance.

Such problems are of course automatically avoided by the use of a single lens reflex camera. The twin lens reflex is not quite so suitable, as there is an appreciable parallax error (page 299) between the twin lenses.

Devices have been developed by Zeiss, Leitz and Kodak with the aim of avoiding these troubles. The basic principle is to fasten to the camera a frame, which may be either a wire bent to the shape of a rectangle or rods sticking out from the camera, whose ends locate the corners of a rectangle. This frame covers the area that is seen by the lens for a particular close-up distance, and any object in the plane of the frame is in sharp focus. The size of the frame, has of course, to be decided according to the focal length of the lens and the distance of the close-up. It is a straightforward application of the methods discussed on page 46 to work out the size of frame for any particular case, or alternatively it is a simple job to determine it practically if a ground glass focusing screen can be mounted on the camera.

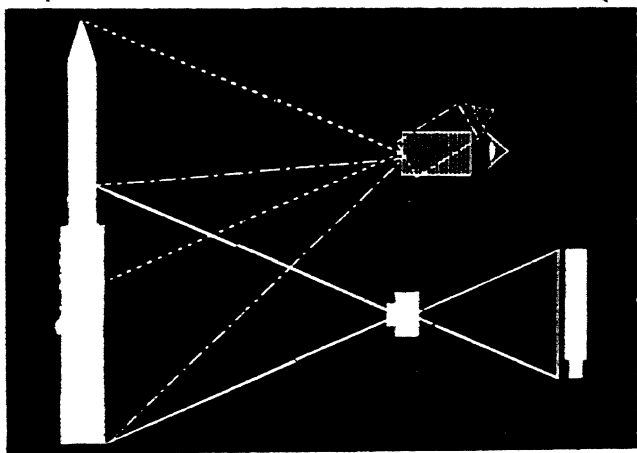
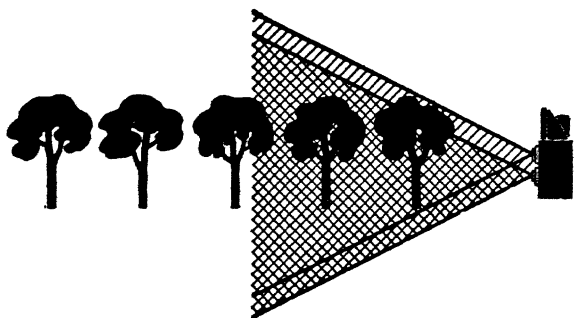
Focus the lens at the required distance on fine lines ruled on plain white paper or card. Then move a pencil point over the paper until it just comes into view on the glass screen. The boundary of the area seen by the lens is soon fixed in this way, and it only remains to fix a frame of metal or wood to the camera in the plane of the paper and of a size indicated by the boundary marked on the paper.

The lens can be focused down to the short distances required by using an adaptor (see page 50) or a supplementary lens (see page 52).

Parallax Errors

The main fault with all view-finders is the introduction of *parallax error*. *The point of view from which they see the scene is not the same point as the forward nodal point of the lens. Consequently they see a slightly different picture to that seen by the lens, just as each eye in normal use sees a slightly different picture.* When the object is at infinity the difference is negligible. But when the lens is used for close-ups the difference may become appreciable.

One way of judging the importance of the effect is this: the separation between the eyes of an average individual



Owing to the separation between the lens and view-finder they see slightly different parts of the scene. When the subject photographed is far away the difference is negligible, but when the finder is used for viewing close-ups the error may become serious leading to cutting off parts of a head and similar faults (*top*). To compensate for this, the parallax error, the view-finder can be tilted as shown in the *lower diagram* (p. 300). There are also other methods of prevention (p. 301).

PARALLAX ERROR

is about $2\frac{1}{2}$ inches. If first one eye is closed, and then the other, an idea is obtained of the difference in appearance of a scene when examined from two viewpoints $2\frac{1}{2}$ inches apart. A few trials will soon show how the difference increases with the approach to the eyes of the picture examined.

In the camera the separation of the two viewpoints is the width between the centre of the lens or the centre of the negative, and the viewpoint of the view-finder. This latter is the centre of the lens in any of the types described above, or the centre of the viewing hole in the simple wire-frame finder. The fact that one viewpoint is further away from the scene than the other is of negligible importance as a rule.

If the separation between the viewpoints is less than $2\frac{1}{2}$ inches the effect of their separation is less than that produced by viewing the scene with each eye separately. If it is greater than $2\frac{1}{2}$ inches the effect is greater.

What has been described above is what can be called the "binocular" aspect of parallax error, and cannot be corrected. At the same time it is of less importance than another aspect of parallax error which can be corrected, as described below.

Not only is the scene viewed from a rather different angle when a view-finder is used, but the area seen through the finder is displaced laterally through the distance between the viewpoints of the lens and the view-finder. This is shown on p. 299.

When distant objects are being dealt with this lateral shift is negligible, but with close-ups and with a physically smaller scene therefore being photographed it becomes of importance. *For a given distance of close-up it can be corrected by tilting the finder as shown on p. 299 also.* The angle of tilt of the finder depends on the distance of the close-up and the separation of the viewpoints of lens and finder. It is given sufficiently closely by this formula.

Angle of tilt = $60^{\circ} \times (\text{separation of viewpoints}) \div (\text{distance of close-up}).$

For instance if the separation of the viewpoints is 3 inches, as shown for instance on p. 299, and the close-up is at a distance of 3 feet (i.e., 36 inches) the angle of tilt is

$$\text{Angle of tilt} = 60^\circ \times 3 \div 36 = 180^\circ \div 36 = 5^\circ.$$

With the type of finder that consists of a sighting hole and a wire frame the parallax correction is most readily obtained by raising or lowering the sighting hole to take it further away from the lens axis. This is in effect the same as tilting the finder. With the preferred type, where the distance of viewing hole from the frame is about equal to the focal length of the lens (depending on the focusing position of the lens), the movement of the sighting hole, away from its infinity position, for close-up use is given by the formula.

$$\text{Movement of sighting hole} = (\text{Separation of viewpoints}) \times (\text{focal length of lens}) \div (\text{distance of close-up}).$$

For instance with a separation of 3 inches between the viewpoint, a lens of 4 inches focus, and a close-up at a distance of 4 feet (i.e., 48 inches) then

$$\text{Movement of Sighting Hole} = 3 \times (4) \div (48) = \frac{1}{4} \text{ inch.}$$

With some types of finder the simplest way is to tilt the finder through the angle needed, as worked out above, but there are various other possibilities.

For instance with a finder that consists of a diverging and converging lens as described above, one method is to rule fine lines on the diverging lens that are unsymmetrically set about the centre line of the finder to allow for this parallax error.

With a twin lens reflex, the separation of the viewpoints is the distance between the centres of the two lenses. *The parallax error due to this can be counteracted by using a ground glass screen that is larger than the plate used. A mask on the glass exposes an area the size of the plate. This mask is movable. When the camera is focused on infinity the mask is in the normal position expected in a reflex camera, and the area of a distant scene thrown on the screen is the same as that recorded on the plate. When the lens is focused for close-up work the mask is slid back through a distance given by*

Movement of mask = (separation of viewpoints) \times (focal length of lens) \div (distance of close-ups).

Range Finders

The principle on which almost all range-finders are built is the same: rays of light from an object go through two windows and form two images. The rays entering the two windows make an angle with each other that depends on the distance of the object from the windows. The relative positions of the two images depend on the angles between the rays entering the windows, and so depend on the distance of the object.

The distance of the object is then measured by measuring the separation of the two images.

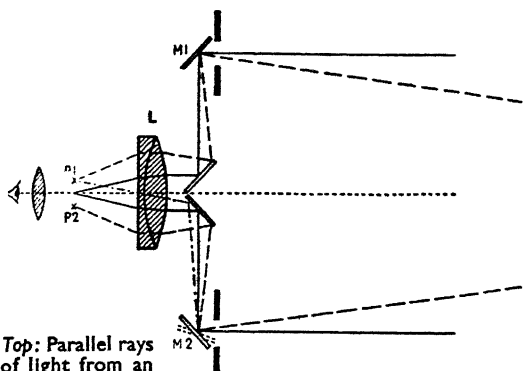
For photographic purposes the separation of the images is measured by finding out what adjustment to an optical system will bring the two images into coincidence.

The simplest type of range-finder uses two mirrors, as shown on p. 303. When the object is at infinity the rays entering the two windows are parallel as shown. And with the mirrors in the positions drawn the rays entering the lens *L* shown are also parallel, and only one image of the distant object is formed.

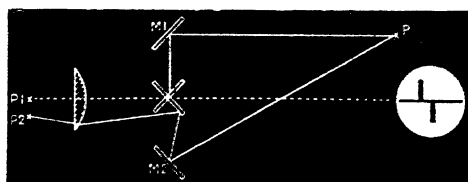
If the mirror setting is unchanged but the object moves into a position nearer the finder the rays of light entering the windows make an angle with one another. They then make an angle with one another when they come to the lens *L*, and this therefore forms two images, at *P1* and *P2* as shown on p. 303. These are examined with the eye lens *E*.

By turning the mirror *M1* through the correct angle, the rays of light leaving it in this second case are turned so that the two sets are parallel when they come to the lens *L*, as shown by the chained line on p. 303. Then only one image is formed, at *P1*.

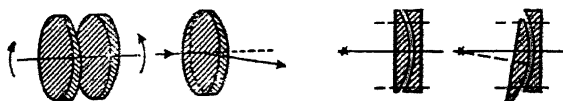
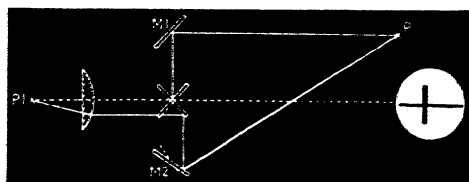
Measuring the distance of an object then means measuring the angle through which the mirror *M1* must be turned, so that the two images seen through the eye lens *E* of the range-finder fuse into one.



Top: Parallel rays of light from an infinitely distant object go through the windows of a range-finder to form a single image. Rays from a nearer point form two images.



Right: By turning one of the range-finder mirrors the two images seen through the range-finder eyepiece are brought to coincidence (p. 302).



Above: By using rotating or swinging wedges a small deviation of the light rays is caused by a larger movement than in the case of a rotating mirror. Hence a larger and more easily produced mechanical adjustment is used to bring the two images to coincidence, and the problem of coupling up the lens focusing to the range-finder adjustment is simplified (p. 304).

RANGE FINDERS

As far as the two images seen through *E* are concerned there are variations in detail. In some cases the field is split into two halves and one half is viewed in effect through each window. The adjustment is made so that the image seen through *E* is continuous, so that one half is not sheared across relative to the other. In other cases, notably in some Zeiss instruments, the silvering of the mirrors is done so that the images reflected from the mirrors *M1* and *M2* are of slightly different colours, one tinged with red, and the other with green. This helps in getting an exact setting. There are quite a number of individual variants on these detailed image arrangements.

The trouble with this simple type of range-finder is the smallness of the angle through which the mirror *M1* must be turned to bring the images into coincidence. The angle of turning away from the infinity position is given by—

Angle of turning = $30^\circ \times (\text{Separation of windows}) \div (\text{Distance of object})$. For instance with windows 3 inches apart and an object 4 feet distant the angle is given by

$$\text{Angle of turning} = 30^\circ \times 3 \div 48 = 1\frac{7}{8}^\circ$$

with an object 6 feet away

$$\text{Angle of turning} = 30^\circ \times 3 \div 72 = 1\frac{1}{4}^\circ$$

and therefore the difference in angle between 4 feet and 6 feet is only $\frac{5}{8}$ of a degree.

Rotating and Swinging Wedges : The aim of several different types of range-finders is therefore to find a method of displacing one image relative to another by a method that is not quite so sensitive to small movements as that just described using a pivoting mirror. Of these methods of swinging light rays through a small distance with an appreciable movement of some mechanical part, two are particularly important, namely, the rotating wedge method, and the swinging wedge.

The arrangement of the rotating wedges is shown on p. 303. The angle of each wedge is very small. The maximum deviation that each can cause is approximately $\frac{1}{2} \times$ angle of wedge. The angle of each wedge is about 5 degrees

giving a range from infinity down to about 3 feet with a reasonable window separation.

When a ray of light goes through the wedge it is bent towards the thick end of the wedge. When this latter is vertical the ray is bent either up or down, according to whether the thick or thin end is uppermost. When the wedge is horizontal the ray is bent to left or right. This is shown on p. 303. With the wedge in between the horizontal and vertical positions the ray is bent up or down and to the side at the same time, so that the total bending is still the same.

In the range-finder two wedges are mounted with the same angle on each. They can rotate in opposite directions, one clockwise, the other anticlockwise from the position in which they are parallel as shown on p. 303 to the position when they are opposed. This means quarter of a turn on each.

When the wedges are parallel they behave as a block of glass with parallel sides and there is no deviation of the light reaching the finder window. When they are opposed the light is deviated to the left or right without any deviation up or down. In any intermediate position the deviation up and down given by one wedge is cancelled by that given by the other, but the deviations to left or right reinforce one another. Consequently in any position of the wedges, when they are correctly adjusted so that each turns the same angle from the parallel position, there is no up and down deviation but simply a side-ways deviation. By putting in the correct amount of deviation in this way the images seen through each window of the range-finder are super-imposed.

If there is any maladjustment of the wedges, so that they do not automatically turn to the same angle as each side of the opposed position there is a residual vertical displacement and the images cannot be brought into exact coincidence.

In the case just described a rotation of each wedge through 90 degrees gives control over a small deviation,

from the full amount when the prisms are opposed, to zero when they are parallel.

The large movement of the wedges for a small deviation helps things considerably in making the range-finder and in coupling it up to the focusing of the lens.

In the second type the deviation is still caused by a wedge or prism, but in effect means are provided to vary the angle of the wedge. The arrangement is shown on p. 303. There are two pieces of glass, one with a plane surface and a concave cylindrical surface, the other with a convex cylindrical surface of the same radius and a plane surface. The glass with the convex surface is free to pivot about the centre of curvature of the curved surface. Consequently the external form of the two glasses can vary from that of a parallel plate to that of a wedge as shown on p. 303. The angle through which the wedge must swing is four times the angle through which a mirror must turn to produce the same deviation.

This type of system has been incorporated by Zeiss in a combined range-finder and view-finder for use on Contax cameras.

The details of the way in which range-finders are coupled to lenses are of mechanical rather than optical interest and are outside the scope of this book.

Stereoscopic Photography

The normal practice is to use both eyes when looking at one's surroundings. This plays a great part in building up an impression of depth, in placing objects at their respective distances, and in giving a feeling of the solidity of things.

The two eyes see the scene from slightly different viewpoints, and as a result the observer is really seeing two pictures at the same time. The optical axes of the eyes also converge slightly to meet in the objects on which attention is concentrated at any instant.

Mental processes fuse the two pictures into one, and provide the sensation of solid relief. And in order to get the full im-

pression of relief it is essential that the mental fusion of the two pictures takes place.

The way in which the use of the two eyes helps to build up our impression of depth and relief is the "stereoscopic effect."

It is lost when plates are taken in straightforward photography. The camera sees things from one angle only. There is no longer the perception of two scenes and their fusion to give a feeling of depth. Skilful lighting and placing of shadows can do a lot towards creating the illusion of depth and solid relief, but it cannot do everything.

To recapture the full sense of the depth of a scene means taking two photographs at a time, a "stereoscopic pair" with a stereoscopic camera. Such a camera has two lenses side by side, so that its action copies that of the two eyes. The photographs, when taken and printed, are examined in pairs, one with each eye, with a stereoscopic viewer.

While the questions that arise when dealing with stereoscopic photography cannot be taken as being of major importance in the total field of photographic optics, there are some points of optical interest that should be dealt with. They arise both in the use of the taking camera and in the use of the stereoscopic viewer.

Taking the Pictures : The first requisite of the two taking lenses is that they should be of the same equivalent focal length and in focus together. The equality of focal length means that the two pictures are on the same scale, and that when the lenses are mounted in the camera panel so that they focus together for one taking distance then they focus together for all taking distances.

Normally there is a variation in equivalent focal length among lenses of the same batch from the factory. As a rule this is something under one per cent. For stereoscopic work however the lenses should be matched to have any discrepancy in focal lengths below this value.

At the same time the position of the face on the lens mount, that locates it on the camera panel, can be adjusted so that both lenses will automatically focus together.

It is important to pay careful attention to depth of field

considerations, since any parts of the picture which are not reasonably sharp cannot be viewed satisfactorily with any true perception of depth.

Brief mention can be made of an alternative taking arrangement using a single camera and single camera lens. In this an arrangement of prisms or mirrors divides the aperture of the lens into two halves and simultaneously separates the viewpoints of these two halves by the correct amount. Two separate pictures are recorded on the one film side by side and these can be printed in the usual way.

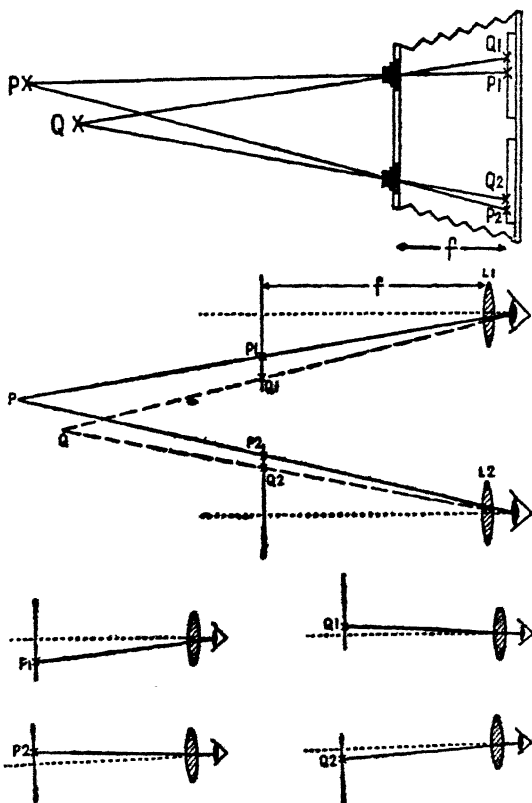
Viewing the Pictures : Suppose now, for example, that taking lenses of 4 inch focus have been used to photograph a distant scene, and that contact prints have been made from the negatives. Suppose further that these prints are mounted as shown on p. 309 one in front of each of two lenses also of 4 inch focus, and in the focal plane of these lenses. Then if the separation of the taking lenses is the same as that of the normal human eyes, and if this in turn is the same as the separation of the viewing lenses, *one can look through the viewing lenses at the prints and see the two scenes exactly as the camera saw them.*

Since the camera lenses have just been specified as being the same distance apart as the human eyes, about $2\frac{1}{2}$ inches, this last fact simply means that when one looks through the viewer one sees just the two scenes that would have been seen by the naked eyes when the pictures were taken. The two pictures seen through the viewer can be fused together in exactly the same way that the original scenes would have been fused, and the same impression of depth is created.

Impression of Depth : The cases of special interest are those in which the separation of the camera lenses is not the same as that of the human eyes, or in which the focal length of the lenses in the viewer is not the same as that of the camera and the effect that these have on the impression of depth.

A measure of the stereoscopic effect is the angle between the rays from any point that enter the two eyes, and the differences between the angles for varying object positions.

Now take a concrete case where the lenses are of 4 inch



Top : The essential feature of stereoscopic photography is that two pictures are taken from two side by side positions. The negatives so obtained differ from one another according to the separation of the taking positions and the distances of the objects photographed (p. 307).

Centre : Two pictures taken with a stereoscopic camera or its equivalent are viewed through a stereoscopic viewer as shown. The lines from the eyes through corresponding prints meet in P and Q and give the impression of depth to the two points, among others (p. 307).

Lower : The best condition is when the eyes converge to P1 and P2. Stereoscopic fusion can be obtained when there is a very slight divergence to Q1 and Q2 (p. 311).

STEREOSCOPIC VIEWING

focal length in both viewer and camera, and the separation of the camera lenses is that of the normal human eyes, i.e., $2\frac{1}{4}$ inches. The separation of the viewing lenses is necessarily this figure. An object 12 feet 6 inches, i.e., 150 inches, in front of the lens panel sends rays to both lenses, as shown on p. 309. For simplicity imagine that the ray through one lens coincides with the lens axis, and that the image of the object formed by this lens is consequently in the centre of the plate. The ray going through the other lens makes an angle of about 1 degree with the lens axis, and the image is displaced $\frac{1}{15}$ inch away from the centre of the negative.

When contact prints are made and examined with the viewer, the ray from the image in the centre of the print coincides with the lens axis. The ray from the image displaced one-fifteenth of an inch from the centre makes an angle of about one degree with the lens axis. As a result there is an angle of about one degree between the rays entering the two eyes, and which are mentally fused to give one image point.

If however the distance between the camera lenses is 5 inches, i.e., twice its previous value, the focal lengths, etc., remaining as before, the image on the plate is now displaced two-fifteenths of an inch away from the centre of the negative. When the prints are viewed under the conditions described above the ray from this point on the print now makes an angle of about 2 degrees with the axis. The angle between the two rays entering the two eyes is thus twice its previous value, and the same holds for the pairs of rays from all other points. As a result the sensation of depth and relief is increased, and objects in the picture stand out from one another in a more pronounced way than before.

Using a camera with a lens separation greater than that of the human eyes, and using a stereoscopic viewer under the conditions described above, magnifies the impression of depth.

The next thing to do is to see what is the effect of using enlargements instead of contact prints in the stereoscopic viewer, and to see what difference is made when the focal lengths of the viewing lenses differ from those of the camera.

When enlargements are used, say for example enlargements in the ratio of 3 to 1, the angle between any pair of corresponding rays entering the eyes is increased threefold. At the same time every object in the picture seems three times as large. The net effect is the same as looking at an object which is three times as large as the original subject in all directions from the same viewpoint. It will be apparent from geometrical considerations that this effect is not the same as looking at the original subject from a camera position reduced to one-third of the actual value of the camera to subject distance.

This is quite a different effect from that met with when using a camera with more widely separated lenses than the human eyes. In that case each object stays its proper size, but there is produced an impression of a more pronounced stretching out, away from and towards the camera.

The effect of using viewing lenses of shorter focus than that of the camera lenses is the same as using enlargements instead of contact prints.

In other words the effects of using enlargements or short-focus viewing lenses are just the same as those encountered in normal photography. What is novel and of importance in stereoscopic photography is the enhancement of relief obtained with widely spaced camera lenses.

The same effect can be produced by taking two photographs with a normal camera, with a lateral displacement of the camera between the two exposures, taking care to keep the camera in parallel positions when the exposures are made.

Mounting the Prints : There are points to notice in connection with setting the prints in the viewer. The first is to make sure that lines joining corresponding points in the two prints are parallel, and that they are parallel to the line joining the centres of the viewing lenses. The second is to place the prints in the correct order, with the left-hand print in the left-hand position on the viewer. The third is to make sure that lines from corresponding points diverge to the eyes as shown on p. 309, and that they do not converge as also shown on p. 309. When the rays are converging

the axes of the eyes are diverging, and although it is possible to fuse the images in this case it is more difficult to do so, and with anything over a slight degree of convergence the fusion of the two images becomes impossible. If any difficulty is encountered in fusing the two scenes with the simple and straightforward kind of viewer normally used, and described in outline above, the fault most likely to be responsible for this is that the rays are converging instead of diverging. It can be overcome by moving the two prints closer together until fusion is obtained.

Stereoscopy in the Cinema

Just in the same way that the stereoscope requires two separate pictures taken from two camera viewpoints, so the viewing of stereoscopic moving pictures in the cinema requires two images projected from two different films. In this case the two images are not positioned side by side but approximately superimposed.

In order to ensure that each eye can only see the image intended for it, polarising filters are inserted in front of each projection lens and the viewer wears polarising spectacles. The axes of the polarising filters are oriented in such a manner that the light from the left eye picture is polarised at right angles to the polarising angle of the right eye spectacle so that the right eye cannot see the left eye picture and vice versa. The screen surface must be metallised—usually with a thin aluminium coating—to avoid loss of polarisation when light is reflected from the screen.

Red and green filters have been used in a similar way to separate the two images, but these are not very suitable and they cannot be used for colour films.

Although two images are projected simultaneously, the light transmission through both sets of filters is so low that the picture appears considerably less than half as bright as normal unless brighter arc lamps or wider aperture projection lenses are used.

The degree of superimposition of the two image points which constitute one point of the object being viewed will

depend upon the distance of that object as seen by the two cameras and hence the convergence of the eyes to fuse these points gives the stereoscopic effect.

Usually a film has to be produced with a particular magnification in mind and to avoid exaggerated stereoscopic effects at this magnification, sometimes the camera separation has to be much less than the human eye separation.

Other proposals for cinema stereoscopy achieve the separation of right and left eye images at the screen itself. These are highly complex and depend on the use of lenticular or similar grids on or in front of the screen. The two images are then split up into vertical strips, and "interlaced" leaving the lenticular grid to present each component picture to the appropriate eye.

Enlarging

Enlarging has been dealt with in another volume of this *Manual* (1), and all that can be done here is to call attention to one or two points of optical interest that arise in connection with the use and construction of enlargers.

The arrangement of negative, enlarging lens, and enlarging board for any magnification can be worked out (p. 54).

The importance of using a lens specially corrected for enlarging conditions has been pointed out on pp. 133, 184.

Illuminating Systems : The illuminating systems of enlargers are of two basic kinds, those that use a condenser and those that rely upon a diffusing screen.

In either case the important thing is to bring up the intensity of illumination at the edge of the negative.

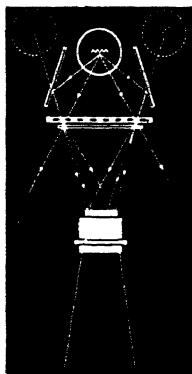
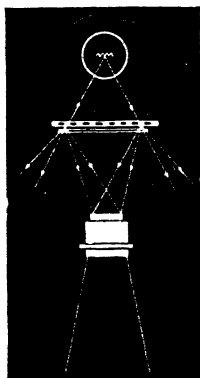
In the condenser type of enlarger the light from the bulb, either of clear glass with a bunched and compact filament, or sometimes a pearl or opal bulb, is collected by the condenser and brought to a focus in or near the enlarging lens. The negative to be enlarged is placed as near as possible to the condenser in order to keep up the marginal illumination, and to keep down the diameter of the condenser needed.

(1) *Enlarging, The Technique of the Positive*, by C. I. Jacobson. (Focal Press.)

The diameter of condenser is just larger than the largest diagonal of negative to be dealt with. As a rule there is no close limit on the focal length of the condenser or its type. If a bunched filament is used the enlarger is not significantly different from a projector as described later in this chapter. The condenser then consists of two plano-convex glasses with their convex surfaces facing one another, and with a plano side nearer the negative, as shown in the diagram on p. 315. The focal length of the condenser is then as a rule about two thirds of the focal length of the enlarging lens, so that when the positions of the principal planes are taken into account a slightly enlarged image of the filament is formed near the front glass of the enlarging lens. This type of condenser illumination is somewhat inconvenient in that the lamp position has to be changed to get the best illumination when the degree of enlargement is changed. A more common form of enlarger-illuminating system employs a condenser and an opal bulb, the diameter of the opal envelope being about two thirds of the diagonal of the negative. The focal length of the condenser is then just less than the focal length of the enlarging lens. The usual form of condenser is again two plano-convex glasses with their convex sides facing one another : a rather better form uses two plano-convex glasses with the convex side of one next to the plano side of the other, as shown *bottom left* on p. 315. In enlargers for dealing with the 24×36 mm. frame a single biconvex condenser is frequently used. With the condenser and opal bulb arrangement no variation in bulb position is needed with different degrees of enlargement, and the position of the bulb relative to the condenser is not critical. What should be noted is that for high degrees of enlargement, with the distance of the enlarging lens from the negative near its minimum value, the lamp recommended by the makers should be used. A lamp of smaller wattage will normally have a smaller envelope, and under the conditions stated this will probably result in poor illumination of the corners of the negative. It should also be noted that a pearl bulb is not an efficient substitute for an opal bulb in this type of enlarger.

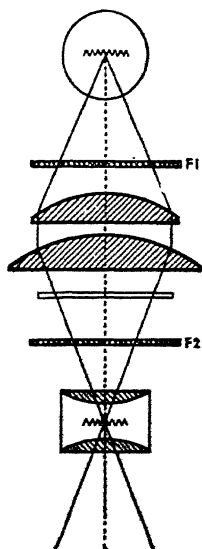
In the type of enlarger that uses a diffusing screen the illumination of the negative is carried out by light transmitted and scattered by a sheet of flashed opal or greyed glass mounted immediately behind the negative. To obtain the best results the diffusing medium must itself be illuminated evenly. This is especially true when greyed glass is used. One method of effecting even illumination is to use a condenser to direct light on to the diffusing screen. Such a condenser may be of larger focal length than a condenser used without diffusion, as discussed above. When large size negatives are to be handled, say whole plates or larger, the use of a condenser becomes impractical. A device that is used in a case such as this, is incorporated in enlargers by *Aldis* and *Kodak*, and consists of a system of sloping mirrors lining the sides of the enlarger lamphouse. Each of these mirrors acts as if there were a lamp behind it throwing light on to the diffusing screen. The evenness of illumination is dependent in this case on careful choice of mirror sizes and angles.

Varying Contrast : One well-known fact is that harder contrast is obtained with a condenser enlarger than with one that relies upon a diffusing screen. This is dealt with in the



Left : The simplest type of enlarger illumination uses a clear or opal bulb and a diffusing screen (p. 314).

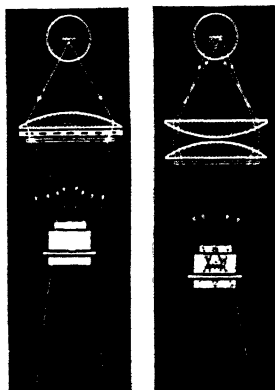
Right : A more even and efficient illumination is obtained by the use of correctly placed mirrors. The mirrors reflect light as if there were two more light sources behind them (p. 314).



Above left : Alternatively efficient illumination is obtained with a clear or opal bulb and a diffusing screen backed by a condenser (p. 314).

Above right : Rather hard contrast is obtained with a clear or opal bulb and a condenser as shown (p. 314).

Left : A variable contrast enlarger patented by Zeiss. F1 and F2 are polarising filters. As F2 is rotated there is a variation in the contrast of the enlarged image (p. 316).



ENLARGER ILLUMINATION

book already quoted, and in another volume of this *Manual* (1). *The explanation is that the silver grains in the negative not only cut off light by absorbing it, but they also scatter the light incident on them.*

With condenser illumination the rays of light that traverse the negative are all going in more or less the same direction, towards the enlarging lens, and any light that is scattered is deviated so that it does not reach the enlarging lens. As a result no light from the opaque parts of the negative reaches the enlarging board, and the contrast is hard.

When a diffusing screen is used the light incident on the negative has already been scattered by the screen and is coming from all directions. As a result some light is scattered by the silver grains in the dark parts of the negative so that it reaches the enlarging lens. The opaque parts no longer seem perfectly black and the contrast is softened.

This is a perfectly well-known phenomena. It is dealt with in the books already quoted, and there is no point in going over the ground again here. What can be described is its application to the construction of a variable contrast enlarger.

The contrast is hardest with condenser illumination, where scattering by the silver grains is unimportant, and softest with a dense diffusing screen, when scattering has to be taken into account. If a means can be found of controlling the proportion of scattered and directly transmitted light then the contrast can be varied within limits. Various methods of doing this, all of them more or less satisfactory, and using stops of particular shapes, have been described. A particularly ingenious method is described by Zeiss in British Patent Specification 535,290.

The method there described is to use a condenser enlarger arranged as shown on p. 313, with a bunched filament lamp. Between the lamp and the condenser is a polarising filter *F1*, and between the negative and the enlarging lens another polarising filter *F2*.

(1) *Developing, The Negative Technique*, by C. I. Jacobson. (The Focal Press.)

This arrangement ensures that the light reaching the negative is plane polarised. The light transmitted directly by the negative has its polarisation unchanged. If $F1$ and $F2$ are parallel all the directly transmitted light goes through $F2$. If $F1$ and $F2$ are crossed none of this light goes through $F2$.

The light that is scattered is depolarised and is not affected by any change in the position of $F2$.

Consequently by turning $F2$ relative to $F1$ the proportion of diffused and directly transmitted light can be varied continuously, and so the contrast in the negative can also be varied.

Only one type of enlarger has been described above, but several other types are described in the patent specification.

One point that should be mentioned is that, with an enlarger using a diffusing screen, the contrast on the enlargement may be slightly softer than that of the image on the enlarging board examined with the naked eye. The blue light acting on the paper is scattered much more than the yellowish-green light to which the eye is most sensitive. The effect as a rule is not of any great importance, nor does it cause much trouble.

Correction of Distortion in Enlargers

When a photograph is taken with the camera axis inclined to the horizontal the most obvious result is that lines which should be parallel on the negative, such as the vertical edges of buildings, are actually inclined at an angle to one another.

For convenient reference this effect produced by an inclined camera can be called "convergence of perpendiculars," since it is most evident in the convergence of the perpendicular edges of buildings in a photograph taken in this way.

It is sometimes stated, without sufficient emphasis on the conditions to be observed, that the convergence of perpendiculars can be corrected when an enlargement is being

made. It is true that the use of a sloping enlarging board, either alone, or taken in conjunction with a tilted negative or pivoted lens, leads to bringing these lines back to parallelism. But in actual fact this is not the only condition to be observed in making a satisfactory enlargement.

Consider a concrete case. A photograph is taken of a square object with the camera sloping up at an angle as shown on p. 320. As a result the image on the plate or film is not a square, but a trapezium. An enlargement is to be made from this negative with these conditions : In the enlargement the sides of the figure shall be parallel to one another, not inclined at an angle ; similarly the figure is to be a square, and not a rectangle as so often happens ; and thirdly the enlargement is to be in focus over its whole area.

There are thus three conditions to be fulfilled.

In general (leaving the case of a swivelling lens for later consideration, see page 326) there are three possible adjustments that can be made. These are : The angle of tilt of the negative in the enlarger, the tilt of the enlarging board, and thirdly there is possible a certain amount of freedom in the choice of the focus of the enlarger lens and the degree of enlargement that it is to give.

While an exact fulfilment of the three conditions stated above cannot in general be established, a suitable choice of the enlarger setting enables quite a good approximation to be made.

In the case of the reproduction of a square quoted above it is a simple matter to see that the proportions of the enlargement are just those of the original scene that was photographed. This example was quoted because it brings out clearly the conditions to be fulfilled in a satisfactory enlargement. In practice however there are not geometrical figures of this type in the photograph by which the correct rendering of proportions can be judged. The best procedure then in discussing the correction of convergence of perpendiculars is to indicate under what conditions the production of the desired parallelism automatically involves the reproduction of the scene in its proper pro-

portions, or to give an estimate of the degree of elongation produced in the enlargement if these conditions cannot be exactly fulfilled.

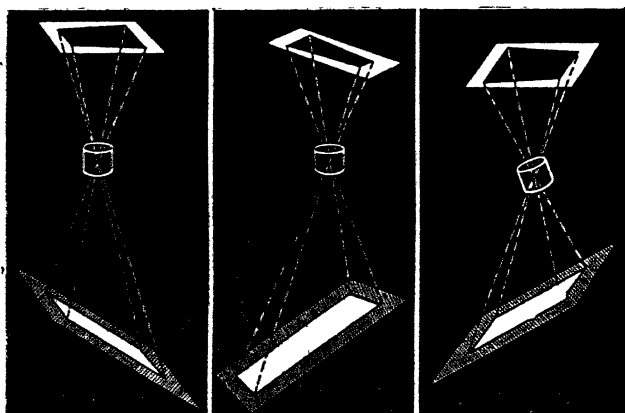
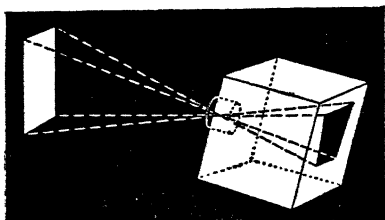
The simplest way in which the perpendiculars are rendered parallel is to keep the negative square on to the enlarging lens, as shown on page 320, and to tilt the enlarging board only. It is a simple matter to tilt the enlarging board through such an angle that the converging perpendiculars are rendered parallel. But at the same time it usually happens that the proportions of the original are not reproduced in the enlargement; a square is reproduced as a rectangle. The picture is much too drawn out in one direction and usually things are too tall and thin, consequent upon the camera being pointed slightly upwards. Also in order to get reasonable definition over the whole area of the enlargement the lens has to be stopped down considerably.

The factor that determines whether or not there is any lack of proportion in the enlargement is the ratio of two distances. The first of these is the distance of the rear nodal point of the enlarging lens from the negative in the enlarger; call this for short the "enlarging nodal distance." The second is the distance of the rear nodal point of the taking lens from the film or plate in the camera; call this the "taking nodal distance." To get proper proportioning of the enlargement when parallelism is obtained by tilting the enlarger board these two distances should be the same.

If the enlarging nodal distance is greater than the taking nodal distance, as usually happens, then the picture is more drawn out than it should be. If the reverse is the case then the picture is much too squat and compressed.

The methods of working out the nodal distances have been fully explained previously (see pages 46 and 52).

The general conclusion to be drawn is that the enlarger lens should be of shorter focus than the taking lens. In normal circumstances where a tilt of the camera is noticeable, e.g., in architectural studies, the subject is at a distance of more than say twenty times the focal length of the lens



Top : A tilted camera photographing a square produces a distorted image (p. 317).

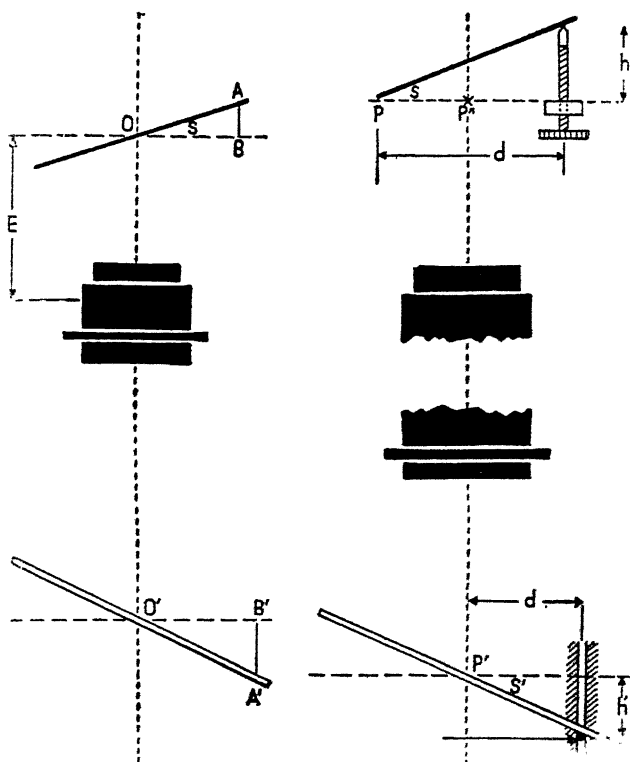
Lower left : It is possible to correct part of the distortion when making an enlargement by tilting the enlarger board (p. 319).

Centre : Or better still by tilting both the negative and the enlarger board (p. 323).

Right : Alternatively the lens may be pivoted and the enlarger board tilted (p. 326).

Unless special care is taken the convergence of the sides of the square is corrected in the enlargement as described above at the expense of drawing out the image that should be a square into a rectangle (p. 319).

PRODUCTION AND CORRECTION OF DISTORTION



Left : Under the proper conditions the distortion in a negative can be corrected by using a tilted negative and enlarging board. An important distance is the enlarging nodal distance E . The slopes of the negative and enlarging board have to be related, as described in the text, to the enlarging nodal distance E and to the taking nodal distance (pages 319, 323).

Right : Practical details of enlarger adjustment are illustrated by which the correct ratio of angles can be established. The conditions that guarantee correct proportions when parallelism is attained involve tangents of angles. Any use of mathematics is eliminated by considering the adjustments to be made in the manner shown. What has to be established then is the correct ratio of the distances d , d' , h and h' , as explained in the text (p. 324).

ENLARGER ADJUSTMENT FOR CORRECTION OF DISTORTION

away, and without serious error for pictorial work the taking nodal distance can be taken as equal to the focal length of the camera lens. The enlarging nodal distance is necessarily greater than the focal length of the enlarger lens ; in the case of a 2 : 1 enlargement it is 1.5 times the focal length, and for a 3 : 1 enlargement 1.33 times the focal length. The general formula is given on page 54.

The difficulty that is encountered with the use of a lens for enlarging of smaller focal length than the taking lens is that it may not cover the whole of the field covered by the taking lens even when it is stopped down. In such a case a useful procedure is to use a wide-angle lens (see page 172) stopped down sufficiently to give good definition all over the sloping enlarging board.

In practice it often happens that the same lens is used both for taking the negative and for enlarging it. In this case it is not possible by tilting only the enlarger board to obtain an exactly proportioned enlargement. The rule in this case is that the greater the degree of enlargement the more nearly correct are the proportions of the enlargement when parallelism is attained.

It is not worth while trying to shorten the focus of a camera lens used in an enlarger, so that the condition about the equality of the nodal distances can be fulfilled, by using a converging supplementary lens. A supplementary lens of sufficient power to be of use upsets in too marked a fashion the corrections of the original lens.

The pertinent mathematical formulæ are :

Focal length of camera lens f : Focal length of enlarger lens F
 Camera lens focused on a distance u : Degree of enlargement M times

Taking nodal distance $T = \frac{uf}{u-f}$: Enl. nodal dis. $E = \frac{(M+1)}{M} \times f$

Call the ratio $R = E \div T$.

The slope of the camera is i degrees

Then the degree of elongation is $\sqrt{\frac{1 + R^2 \tan^2 i}{1 + \tan^2 i}}$

A rough rule giving the f /number of the lens aperture so that it will give a circle of confusion of less than .01 inch at any point on the enlarging board is this : if the edge of the enlarging board is raised or dropped d inches away from its square-on position, if the degree of

enlargement is M diameters, then the f /number f/N is given by $N = 100d \div (M + 1)$.

Thus for a 10 times enlargement with $d = 2$ inches $N = 2 \times 100 \div 11$, i.e., N is approximately 18, and the lens should work at about $f/18$.

In a more sophisticated use of the enlarger to correct the convergence of perpendiculars both the negative and enlarging board are tilted as shown on p. 321.

By matching together the tilt of the negative and that of the enlarging board the correct proportions can be guaranteed when the parallelism of the perpendiculars is established. In carrying out the enlarger adjustment there are two factors that have to be related to one another. The first is what can be called the "tilt ratio" of the enlarging board and negative, which measures the slope of the enlarging board compared with that of the negative. The second is the ratio of the enlarging and taking nodal distances already defined.

The relative tilts of negative and enlarging board are measured not by the ratio of the angles that these make with their square-on position, which they occupy in normal enlarging work, but by the tangents of these angles. What this means is shown on page 321. AB is the height of a point above its square-on position. OB is the distance of the point from the axis about which the negative pivots. This latter in the case drawn on p. 321 is on the lens axis. The distance OB has to be measured along the square-on position and not along the sloping negative; this is also shown. The negative makes an angle of s degrees with its square-on position. Then the tangent of s , written $\tan s$, is $AB \div OB$. Similarly for the enlarging board the tangent of s_1 , written $\tan s_1$, is $A_1B_1 \div O_1B_1$, as shown on p. 321. E is the enlarging nodal distance referred to already.

Suppose that the taking nodal distance is T . (As a rule it is very closely equal to the focal length of the taking lens. In actual fact it is the v worked out as described on p. 48.) The ratio R of the enlarging and taking nodal distances is $E \div T$.

Then the condition to be established in order that both

correct proportions and parallelism of perpendiculars can be guaranteed is

$$\tan s_1 = \frac{R^2 + 1}{R^2 - 1} \times \tan s.$$

In general it will still be necessary to stop down the lens to get good definition over the whole of the enlargement.

A concrete example of the carrying out of the enlarger adjustment in the fashion indicated will make things clearer.

Suppose that a photograph is taken with a lens of 2 inches focus, and that the lens was focused for infinity when the exposure was made, then the taking nodal distance is just equal to the focal length of the lens, i.e., 2 inches.

An enlargement is to be made, in the ratio of 5 : 1, with a lens of 3 inch focus, then the enlarging nodal distance (see page 56) is 3 inches $\times (5 + 1) \div 5 = 3.6$ inches.

The pertinent ratio R is thus $3.6 \div 2 = 1.8$ and the value of

$$(R^2 + 1) \div (R^2 - 1) \text{ is } (1.8^2 + 1) \div (1.8^2 - 1),$$

$$\text{i.e., } (3.24 + 1) \div (3.24 - 1) \text{ or } 4.24 \div 2.24 = 1.89.$$

Then for any setting of the negative by tilting it through an angle s the enlarger board should be tilted through such an angle s_1 that $\tan s_1 = 1.89 \tan s$. This can be arranged without recourse to mathematical tables in the following way, which also indicates the general principle to be followed in making the enlarger adjustments.

Suppose that the tilt of the negative is adjusted by a screw as shown on p. 321, where the negative carrier, or even the negative itself, pivots about an axis through the point P shown. The distance from this point to the centre of the adjusting screw is d . The height through which the end of the screw raises the negative is h . Then the tangent of the angle s is $h \div d$. If for instance the distance d is 2 inches, then $\tan s = h \div 2$ or $\frac{1}{2} h$. It is preferable if possible to have the pivoting point or axis P on the lens axis at P'' , as in this event there is no need to re-focus the enlarger as the negative is tilted. If P is not at P'' then a re-focusing is needed as the negative adjustment is changed.

As far as the adjustment of the enlarging board is concerned it is of more importance that the axis about which it swings should be on the lens axis. Otherwise the effective overall distance from negative to the centre of the enlarging board changes rather rapidly as the board is tilted with a consequent change in the degree of enlargement, so upsetting the calculation made to ensure correct proportions. If then the pivot is not on the lens axis the negative and enlarging lens must be moved at each setting of the enlarger board to give the correct degree of magnification. While this same effect is present in the case of the negative tilt it can be neglected here as a rule since the change in overall distance it produces is normally quite small. In the figure shown, if the tilt of the enlarging board is controlled by a bar supporting it which travels in a vertical slot, and the drop is h^1 for an offset distance d^1 , then $\tan s_1 = h^1 \div d^1$.

Suppose that in a particular case $d^1 = 10$ inches. Then

$$\tan s_1 = (1/10) h^1.$$

Comparing this with the figures given above for the negative tilt the base h^1 is five times the base h (i.e., 10 inches and 2 inches). Hence to produce the same tangent at P^1 as at P means that the drop of the bar h^1 must be five times the elevation h given by the screw.

Hence to produce the required ratio of the tangents, viz., 1.89, the drop of the bar h^1 must be $5 \times 1.89 = 9.45$, or near enough 9.5 times the elevation h produced by the screw that raises the negative.

To get the correct setting of negative and enlarging board start from the position where both are square on to the lens axis, and the perpendiculars in the enlargement are convergent. Raise the negative by means of the adjusting screw through a definite distance, say .05 inch, and drop the enlarging board through $9.5 \times .05$, i.e., .475 inch. Probably this will not be sufficient. A certain amount of re-focusing may be needed, and it will then be found that the perpendiculars are still convergent. This process of adjusting the two heights in the correct ratio has to be carried out until the perpendiculars are parallel. When this happens the enlargement is correctly proportioned.

It will be necessary to stop the lens down to get good definition over all the enlargement. This latter is in sharp focus when the enlarging board is dropped through 25 times the elevation given to the negative, so that the tilts are in the ratio 5 : 1.

There are one or two points worth mentioning. When the ratio R is equal to 1 then the negative should be kept square-on to the lens axis and only the enlarging board tilted. This has already been dealt with. When R is less than 1, as may happen with an enlarging lens shorter than the taking lens in focus, the negative and enlarging board have to be tilted in the same direction, instead of in opposite directions as they have been drawn throughout in the diagrams. This is distinctly unfavourable for obtaining good definition and requires a very severe stopping-down of the enlarging lens.

To get sharp definition in the enlargement the requirement is that

$$\tan s_1 = M \tan s$$

where M is the degree of enlargement.

In general this is not consistent with the requirement that

$$\tan s_1 = \frac{R^2 + 1}{R^2 - 1} \tan s,$$

and hence correct proportions and sharp definition without stopping down cannot be obtained together.

They can be obtained together only in the special case where the focal length F of the enlarging is related to that

of the taking lens, f , by the formula $F = f \times M \div \sqrt{M^2 - 1}$, or alternatively the magnification M is given by the formula

$$M = \sqrt{\frac{F^2}{F^2 - f^2}}$$

Thus if $F = 3$ Inches, and $f = 2$ Inches

then $M = \sqrt{\frac{9}{5}} = 1.34$. When this is the case the image

on the sloping enlarging board is both correctly proportioned and in sharp focus, and the tilt required to give the correct proportioning in the way already described is just that required to give a sharp focus all over the enlargement.

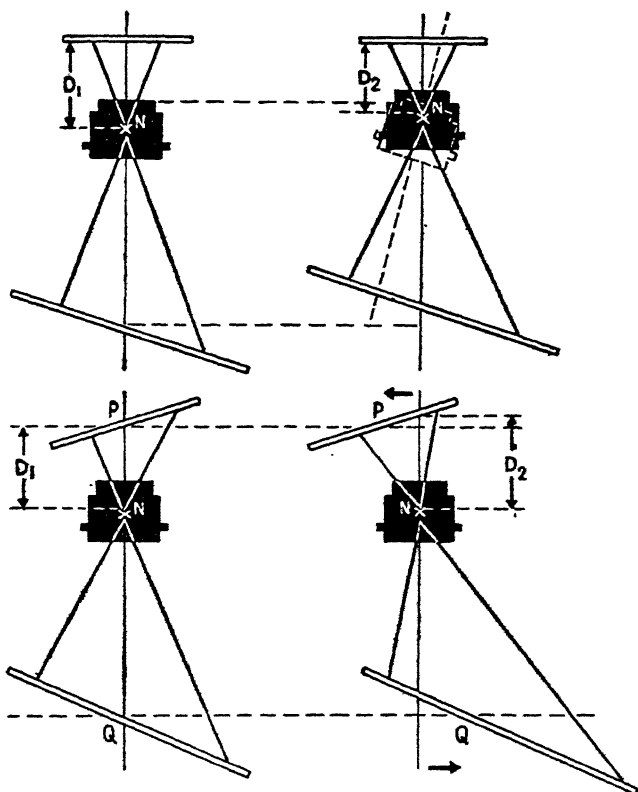
A case of special practical importance is that in which the same lens is used for taking the negative (in which case it is assumed to be focused for infinity) and for producing the enlargement with a magnification of M diameters. Then $R = (M + 1) \div M$, and the ratio $(R^2 + 1) \div (R^2 - 1)$ is equal to $(2M^2 + 2M + 1) \div (2M + 1)$. The general rule is that in this case the greater the degree of enlargement the sharper is the enlargement when parallelism and correct proportioning are established, and the less the stopping down of the enlarging lens that is needed.

A similar type of convergence of perpendiculars is produced when a swinging back is used in the camera but the conditions of remedying it in an enlarger are not the same. This case is of less importance than that just dealt with, and for details works specifically concerned with enlarging should be consulted.

The methods, both the exact and approximate ones, which have been discussed in the pages above, have assumed that the distance from the nodal point of the enlarging lens to the negative, measured along the lens axis, has been related to the focal length of the lens F , by the formula

$$d = (M + 1) \times F/M$$

where d is the distance in question. There are two methods, the same in principle but differing in detail, which sacrifice this requirement and yet provide a reasonable standard of definition over the enlargement. The first is that involving the use of a tilting lens ; the second is that recently



Top : The degree of elongation or compression in an enlargement when verticals are made parallel depends essentially on the distance D shown. Normally D is fixed by the degree of enlargement and the focal length of the enlarging lens. By using a tilting lens a third factor, its tilt, is introduced and the proper value of D may be chosen. A tilting lens provides an approximate, not an exact method of correcting the distortion (p. 328).

Bottom : Another approximate method is that due to *David Charles*. Basically it is the same as the tilting lens method in that the distance of the negative from the lens is varied independently of the focal length of the lens and the degree of enlargement. The variation, however, is effected by sliding a tilted negative, and the magnification is kept constant by sliding the enlarging board (p. 328).

METHODS OF CORRECTING DISTORTION

described by *David Charles*. They are considered below in this order, but it is worth pointing out at this stage that they are both approximate methods only, and not exact in the sense of that term as used in the previous discussion.

1. The angles involved in tilting the negative and enlarging board relative to one another depend on the original camera tilt, the focal length of the taking lens, and the distance of the nodal point of the enlarging lens from the negative. This latter may be measured along some arbitrary fixed line, not necessarily coinciding with the lens axis. The relative proportions when parallelism is established, depend only on the relative tilts and the camera tilt. If the enlargement is of the wrong proportions, either too compressed or too elongated, the distance of the lens from the negative is varied, the distance of the enlarger board is also changed to provide the same degree of enlargement without regard being taken for the moment to the standard of definition. The enlarging board tilt is varied again to ensure parallelism, and finally the lens is tilted about its back nodal point, so that its axis lies along a line such as that shown dotted in the upper right diagram on p. 327. By such a tilt the distance of the nodal point from the negative, measured along the lens axis, is so adjusted that the definition is made fairly even over the whole of the enlargement. In the simplest case the enlarging board only is tilted, and the enlarging lens is moved along a line at right-angles to the negative. In such a case the requirement for there to be no elongation when parallelism is established is that the distance D shown in the upper diagram on p. 327, should be equal to the focal length of the taking lens.

2. In the *Charles* method an adjustment is made, as shown in the lower diagrams on p. 327, so that parallelism is established and the definition made even all over the enlargement. The latter is then examined to see how its proportions are, whether it is elongated or not. In general the proportions will not be correct. In this case the negative is moved in one direction, for instance as shown in the

lower right diagram on p. 327, and the enlarging board moved in the opposite direction. Notice that the points *P* and *Q* about which the negative and enlarging board may pivot remain in the same plane. In general it will be found that parallelism has been upset. This may be rectified by tilting either the enlarging board or the negative, or both. As a first approximation it may not be necessary to perform any re-tilting, as the lack of parallelism introduced may not be noticeable. A certain amount of stopping down may be needed, as the method is essentially a brilliant approximation rather than an exact method of satisfying the laws of optics.

Projection

Although there are methods of making colour prints, up to the present the main trend of amateur colour work has been to make colour transparencies and project them. This has been done especially where miniature work has been concerned, on 35 mm. film, where the introduction of projectors specially designed to project a picture 24×36 mm. has done a lot towards making it popular. These miniature projectors are much more compact and portable than the older lanterns taking $3\frac{1}{4}$ inches \times $3\frac{1}{4}$ inches slides, and this is a particularly important feature for amateur use.

The principles of the operation of both full-size lanterns and miniature projectors are the same. The layout common to each is shown on p. 331.

Light from a bunched filament lamp, specially designed for this class of work, is collected by a mirror *M* and a condenser *C*, and directed through the transparency *T*. It is brought to a focus in the projection lens *P*, or near this lens, and is then brought to the image on the screen *S*. The projection lens is arranged so that it focuses the transparency sharply on the screen with the aid of the light whose path has been described.

That is the bare outline of a projector. The successful working from an optical point of view depends on attention to details of the condenser and lens design, and in some cases to proper matching of these two.

Brightness of the Projection : Projection lenses have already been described on pages 144-150, so that the only thing to take up is the importance of the f /number of the projection lens for the brightness of the projection.

The best way of judging what will be the brightness of illumination at any point on a screen is to imagine one's eye looking from that position towards the sources of light illuminating the screen. The light coming to the point depends on two things : firstly the fraction of the visible area, as seen by the eye placed at the screen, that seems brightly lit, and secondly the individual brightness of each of the lit-up areas seen by the eye.

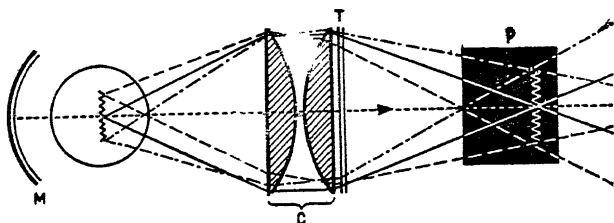
Now In the case of projection the illumination on the screen is derived solely from the projection lens. Hence, in view of what has just been said, the method of judging the brightness of the projection is to look from the screen to the projection lens and see to what extent the full aperture of the lens is filled with light.

The maximum illumination of the screen is obtained when an eye placed at a point on the screen sees the whole of the lens aperture filled with light.

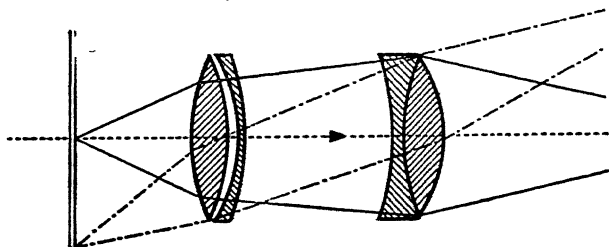
Consider the concrete case of a 4 Inch $f4$ projection lens, with a separation of 48 inches between the lens and the screen, and consider only the illumination in the centre of the screen. To a sufficient approximation this arrangement can be taken as meaning a picture on the screen eleven times the size of the transparency.

When the condenser system is designed to give the most efficient illumination an eye placed at the screen sees a disc of one inch diameter filled with light. The illumination at that point is the same as if an area of glowing filament 1 inch in diameter were placed at the front of the lens, i.e., at a distance of 48 inches from the screen.

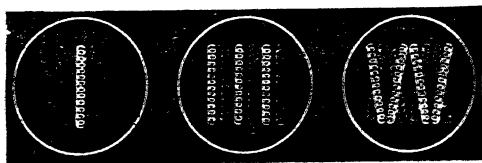
If the lens is of 6 inch focus, still of aperture $f4$, and at a distance of 72 inches from the screen, the picture again will be eleven times the size of the transparency. Under conditions of maximum efficiency an eye placed at the screen now sees a disc of light 6 inches $\div 4$, i.e., $1\frac{1}{2}$ inches diameter.



In the most common type of small projector, one using a filament lamp, a rear reflector forms an image of the filament in its own plane, and the condenser forms an image of these two in or near the projection lens, so that this image fills most of the projection lens. To keep the condenser diameter down the slide or film should be placed as near as possible to the condenser (p. 333).



The beam of light that comes from a point away from the lens axis or centre of the slide, and one which produces the image of this point on the screen, is more restricted by the metal of the lens mount than the beam coming from the centre of the slide. As a result less light is transmitted to form the image of the non-central point and this latter is not so bright as the image of a central point. The disparity depends to a certain extent on the design of the projection lens (p. 333).



The filament in a lamp designed for use in a projector lies in a plane, as shown in the diagram on the left. The mirror at the rear forms an inverted image of it in its own plane. When the rear reflector is properly adjusted the filament and its image are interlaced, as shown on the right (p. 334).

PROJECTOR ILLUMINATION

The illumination at that point is the same as if an area of glowing filament $1\frac{1}{2}$ inches diameter were placed 72 inches from the screen.

The illumination produced at the screen is the same in both cases. In the second instance where a 6 inch lens is used the larger diameter of the disc of light is offset and balanced exactly by its greater distance from the screen.

The conclusion can thus be stated : for a given degree of enlargement from transparency to projection, the maximum illumination on the screen depends only on the f/number of the lens, and not on the focal length.

Increasing the f/number from f 4 to f 5.6 means that the disc of light is smaller in the ratio of $(4/5.6)^2$, i.e., $\frac{1}{2}$, and for f 8 it is smaller in the ratio $(4/8)^2 = \frac{1}{4}$ (Areas are the significant features, not diameters). Thus, in the first case the illumination is reduced to half its earlier value, and in the second case to one quarter of its previous value. This shows the importance for a bright projection of having a small f/number and a large aperture.

If instead of an eleven times enlargement it had been a 14 times increase from transparency to projection the intensity of the screen illumination would have been reduced in the ratio $(12 \div 15)^2$, i.e., to 64% of its previous value.

The other factor to be taken into account is the brightness of the disc of light seen by the eye. It is a familiar fact that as a higher voltage is put through a lamp the filament seems brighter. It starts from a dull red colour, through cherry red to a bright glowing wire, and after this although no colour change is seen it seems to glow more intensely as it is over-run. It is just this subjective brightness that is referred to as governing the intensity of the projection.

The important fact is that the disc of light seen by the eye at the screen can in no circumstances appear brighter than the filament from which the light is derived.

Therefore, if the lens aperture is fixed and it is required to increase the screen illumination, the only thing to do is to increase the brightness, or "intrinsic luminosity" of the lamp filament, so that it will in turn increase the brightness of the light disc seen by the eye.

Modern projection lamps are run at voltages from 50 to 250 volts, and up to about 500 watts current consumption.

They give what is about the maximum filament brightness compatible with a reasonable filament life. In special cases the brightness can be increased by over-running the lamp, but this is not advisable except as an emergency measure. If a higher intrinsic luminosity is needed an arc must be used.

Even in the ideal case, where an eye placed at the centre of the projection would see the whole of the projection lens filled with light, the illumination falls off from the centre to the edge of the projection. This is due to vignetting in the lens, and the way in which it comes about is shown on p. 331, which illustrates how some of the rays that should reach the edge of the projected picture are intercepted by the lens mount. Such a falling off in intensity of marginal illumination is inevitable, but it can be reduced somewhat by a special design of lens, such as that used for some ciné-projection lenses having a short back focus.

Lamp and Condenser Design: The above limitations are those which are found with even a perfectly efficient condenser system. To them must be added the effects of difficulties with lamp and condenser design.

The ideal thing would be to have a light source consisting of a small metal disc raised to white heat, and with the aid of condenser system to form an enlarged image of this in the projection lens, so that the whole of the aperture of this latter could be filled with light.

An approximation is the zirconium arc developed in the U.S. during the war by *Western Union*. Another approximation is the *Solid Source* lamp also developed during the war by the *Siemens Company* in Britain. Projectors embodying these new sources, of which the second is probably more important, have not yet appeared on the market. Full advantage cannot be obtained from either source except in projectors specifically designed to make use of it.

In present practice the filament consists of a number of strands of closely coiled wire, all arranged in one plane, and having the shapes shown on p. 331. The aim of the condenser system is to form an enlarged image of this in the projection lens.

To increase the efficiency of the system the lamp filament

is placed at the centre of a concave mirror which produces an inverted image of the filament in its own plane, the image being interlaced with the filament as shown by the lighter lines on p. 331.

One of the projection adjustments to be examined, if there is any doubt about the efficiency of the illumination, is the correct alignment of mirror and lamp filament. There are two images formed by the projector optical system, one of the filament itself, and the other of the filament image as formed by the concave mirror. They can be distinguished from one another by the lower intensity of the image of the filament as reflected by the concave mirror. With filament and mirror correctly aligned the images are the same size and interlace as shown on p. 331.

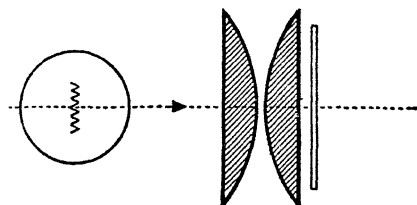
In most projectors it is a simple job to adjust the mirror to the correct position, and as a rule adjusting screws are provided for this purpose. In others arrangements are made whereby slight adjustments of the lamp can be made to ensure correct alignment.

The two images of the filament, i.e., the image of the filament itself and of its image produced by the reflector, can usually be seen quite easily by running the projector with no slide in and stretching a fine handkerchief across the front of the projection lens. Alternatively the images can be focused on the projection screen with a weak supplementary lens. In many cases such a lens is supplied with the projector. The focal length of the supplementary lens is not critical and a 2 diopter spectacle lens will serve very well on the majority of occasions.

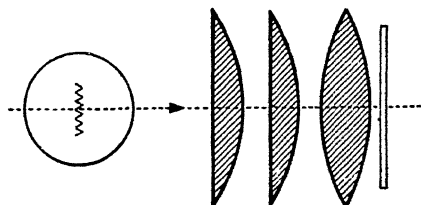
An enlarged image of the filament is formed in or near the projection lens by the condenser system. The problem to be faced in doing this is to keep down the spherical aberration of the system. Various types of condenser have been adopted for this purpose. The orthodox lantern slide type consists of two plano-convex lenses with their convex surfaces facing one another as shown on p. 335. A more recent form of three glass condenser as used especially in miniature work is also shown on p. 335.

It is mainly the spherical aberration of the condenser that fixes the wattage of the lamp to be used in normal projection work, apart, of course, from the considerations of lens aperture and degree of enlargement that have already been dealt with.

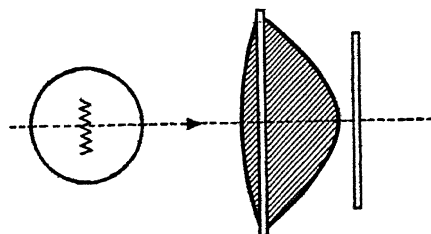
Suppose for example that the lamp filament, of the shape shown on p. 331, can be enclosed in a square $\frac{1}{2}$ inch by $\frac{1}{2}$ inch, that the front of the projection lens has an aperture of $1\frac{1}{4}$ inches, and that the image of the filament formed by the condenser system is to fill the projection lens aperture. The image formed by the condenser is thus to be six times



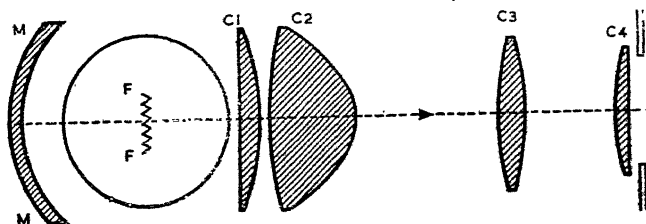
Left top : The orthodox condenser system for slide projection consists of two equal plano-convex glasses with their convex faces next to one another (p. 333).



Centre : A better correction for spherical aberration is obtained in some modern miniature slide projectors by using three glasses. This results in a more efficient condenser system and the lamp wattage can be reduced compared with that needed for the same projection brightness when the earlier form described above is used (p. 333).



Lower : Alternatively the condenser's spherical aberration can be considerably reduced by using non-spherical surfaces, and again a particularly efficient condenser system is produced (p. 333).



For certain 16 mm. projectors a more complex form of condenser system is sometimes adopted, as in the B.T.H. 16 mm. projector (p. 336). (Note that the diagram is not drawn to scale and shows the general arrangement only.)

PROJECTOR CONDENSER SYSTEMS

the size of the original. With a reasonable distance from condenser to the front of the lens this means a short focus condenser, and one with rather deep curves on the glasses. Quite considerable aberrations are present in such a form of condenser and may make the illumination quite uneven, producing the characteristic effect of a dark ring in the field.

The orthodox method of making the illumination more even in a case of that type is to use a longer focus condenser, producing a smaller degree of enlargement of the filament, and a larger filament, so that the size of the filament image is the same as before. Such a filament naturally consumes more current than the smaller filament and produces the same illumination as the smaller filament.

The three lens condenser as shown on p. 335 uses shallower curves than the two glass condenser, and as a result the aberrations are smaller. A shorter focus condenser can be used and a more efficient illumination system produced.

Another type of condenser is the non-spherical condenser used in a *Neokon* projector made in Germany, and shown on p. 335. With the non-spherical form the aberrations can be controlled very carefully, and a surprisingly bright projection obtained with a low current consumption.

At the present time there are few, if any, miniature projectors on the English market using non-spherical condensers. A non-spherical condenser is used in the American *Viewlex* projector.

The condenser systems of 35 mm. projectors for cinemas are outside the scope of this book. For 8 and 16 mm. projectors condenser systems may be used of a similar type to these just described. More complex systems are often required, however, to allow a reasonable separation between the lamp and film gate so that the film transport mechanism may be introduced into the projector. A particularly efficient system, employing an aspheric condenser, is that adopted in the *B.T.H.* 16 mm. projector and shown on p. 335. The filament *FF* of the projection lamp is imaged by the heat-resisting condenser *C1* and the aspheric condenser *C2* on the bi-convex lens *C3*. *C3* in turn images the condenser *C2* on *C4* which is next to the film gate as shown. *C4* images the lens *C3* in the entrance pupil of the projection lens *L*. The light-gathering efficiency of the system depends on the use of the aspheric condenser *C2*. The latter must

have a good surface finish and be free from internal defects since it is imaged near the plane of the film.

Testing Projectors : In testing out an actual projector the best way is to place an empty slide holder in the projector and focus on the edges of this. The quality of the screen illumination is then immediately evident.

If the illumination is much brighter in the centre of the field than at the edge of the field, and if in particular there is strong vignetting at the edge of the picture frame, the lamp filament is too far from the condenser.

If an out of focus image of the filament is formed on the projection screen the filament is much too near the condenser.

If there is a dark ring on the screen the filament is again too near the condenser.

The thing to do is to balance the filament position so that there is neither vignetting nor the formation of a dark ring. When this is realised the filament is correctly adjusted as far as its distance from the condenser is concerned.

If the illumination at top or bottom, or on either side is uneven the filament is either too high or too low, or displaced to one side. If the illumination at the top of the projection is poor the filament is too high, if the illumination at the bottom is poor the filament is too low, and so on.

The adjustment of the mirror has already been dealt with on page 334.

It usually happens that a variety of lenses of different focal lengths can be used in a projector with the same condenser system, but for most efficient use it is preferable and advisable to use a different condenser when there is an appreciable difference in focal length of the projection lenses used. In the case of miniature projectors using three glass condensers this variation of the condenser focus is effected by using a weaker equi-convex lens for projection lenses of longer focal length. In the case of the two lens condenser a new system has to be used as a rule.

Film Viewers

Negatives of the standard miniature size, i.e., 2.4×3.6 cm.,

or negatives taken on film with a smaller picture area, such as micro-film records on 35 mm. film, have to be enlarged and magnified before they can be examined with ease and comfort. An arrangement for viewing such small negatives in comfort is a "film viewer."

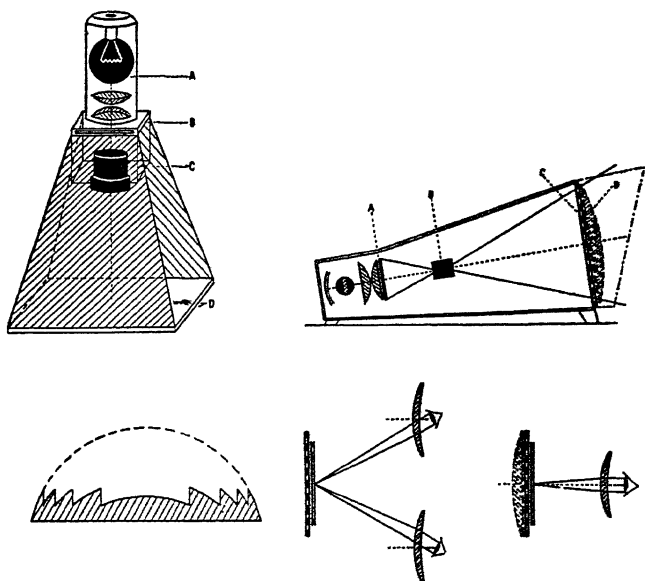
Film viewers can be divided into two classes, namely, those in which an enlarged image of the negative is projected on a screen, and those where it is perceived through a lens.

A film viewer in which an enlarged image is thrown on a screen is identical in performance and intention with an enlarger, differing in only one or two minor points.

In the first place, a film viewer is commonly used in a lighted room and therefore the screen on which the projection is thrown should be well shaded. Also the brightness of the projection is apt to be of greater importance than in an enlarger, without quite such critical standards placed upon its quality of definition. It is therefore preferable to use a lens of moderately wide aperture, say $f2.8$ or $f3$.

In the second place it may happen that the image is thrown on a ground glass screen through which it is viewed. There is of course a reversal from left to right in this case, a matter which is either of slight importance or can be remedied by putting the negative in the viewer the reverse way round to that in which it is put in a projector or enlarger. What is of more importance is a feature sometimes found with this instrument, namely, that either the ground glass is rather dense, giving an image that is rather dull but evenly illuminated right into the corners of the negative, or else it is too thin and gives a brighter image but one in which the centre is much brighter than the corners and in which it may be necessary to move one's head to the side to see the image at the edges and corner of the screen sufficiently brightly.

In this second case the trouble can be alleviated somewhat, without decreasing the brightness of the image, when the projected picture is, say, less than 6 inches from corner to corner diagonally, by using a condenser such as is mounted in a condenser-type enlarger, or in some projectors. It acts in exactly the same way as the lens placed on the ground



Top left : The essential features of a film reader of the projection type. They comprise a lamp A, a condenser B with the film immediately in front of it, a projection lens C, and a reading board D. This latter is shielded from stray light by the box-like structure round three sides of it. The similarity to an enlarger will be apparent (p. 338).

Top right : By turning the reader just described on to its side, and by using a translucent screen in place of a reading board, a new form is obtained which it is sometimes more convenient to use. With this form the evenness of the illumination can often be improved by mounting a condenser lens D against the screen as shown.

Bottom right : The simplest type of viewing, as distinct from projection, film reader consists of a holder for the slide or film and a magnifying glass. Occasionally a condenser lens and diffusing glass are mounted behind the film to even up the illumination. For prolonged use the projection type induces less fatigue (p. 337).

Bottom centre : One of the difficulties to be overcome in using both eyes with a viewing type of reader, is that the eyes have to converge unduly with the simplest type of apparatus, and there is too much strain for continued use. The way in which the eyes have to converge is shown in the diagram (p. 341).

Bottom left : The field viewing screen is equivalent to a lens the outline of which is shown dotted (p. 340).

FILM READERS AND VIEWERS

glass in a "brilliant" view-finder (see page 296). The shorter the focal length of the condenser the more efficient it is, within limits, in bringing up the brightness of the edges and corners of the projection. The aberrations of the condenser set a limit on the shortness of the focal length, and the minimum value that is useful is about $2\frac{1}{2}$ to 3 times the diameter of the condenser.

A more satisfactory way of obtaining an even illumination in a viewer of this type (or in a reflex camera where the problem is to obtain a picture of even brightness on the focusing screen) is to use a *field viewing screen*. The basic form of this is shown on p. 339. It can be regarded as a lens in which successive parts of the convex surface have been moved back nearer to the plane surface. These elements retain their power to bend light in a suitable way, but their new positions mean that the bulk of the lens is considerably reduced. In actual practice the curvatures on the faces of successive elements are neglected and the latter are made small, about .005 inches wide or less. The screen is moulded from plastic, the die for the refracting surface being cut by a tool following a special path and varying its inclination to the surface in a systematic way. By the use of this screen all the benefits of a deep collective lens may be gained with an over-all thickness of a few hundredths of an inch. The pitch of succeeding elements is so fine that the spiral pattern is not obtrusive at normal viewing distances.

The arrangement of the second type of viewer is shown on p. 339. A magnified image is viewed through the lens. The degree of enlargement need not be great. For all practical purposes a magnification of $2\frac{1}{2} \times$ to $3 \times$ is quite sufficient. This means that the focal length of the magnifying lens should be from about $3\frac{1}{2}$ inches to $4\frac{1}{2}$ inches or about $+10$ to $+14$ diopters. The shorter the focal length the greater the magnification the lens produces; an approximate formula is $\text{magnification} = 10 \div (\text{focal length})$, where the focal length is measured in inches, or $\text{magnification} = (\text{Power in diopters}) \div 4$.

The shape of the magnifying lens is of importance. The lens tends to suffer especially from astigmatism, and the ratios of the curves have to be chosen to reduce this to a minimum. The exact shape is not critical in the way that the shape of a glass in a photographic lens is determined within very close limits. The preferable form is a meniscus lens as shown on p. 335, with the concave surface towards the eye.

Failing such a form, the next best thing is a plano-convex lens with the plane side towards the eye. Either type described is greatly to be preferred to the ordinary type of magnifying glass, which is simply an equi-convex lens, having rather pronounced astigmatism

It has been implicit in what has been said above that only one eye has been used in looking at the transparency or print that is being examined. It is possible to use two magnifying glasses, one in front of each eye, to look at a single print, but this as a rule involves considerable eye-strain.

The difficulty is due to the fact that there are two adjustments of the eye that have to be taken into account, and which cannot be carried out independently except under conditions of strain. These two adjustments are "accommodation" and "convergence." The adjustment by which the eye is refocused when the object of its attention moves from a great distance to a near position is the "accommodation" of the eye. Muscles in the eyeball change the shape of a flexible lens, and so change its focal length to the extent needed to focus any particular object upon the retina. With normal sight the limiting distance with which the eye can deal in this way is about ten inches. The change of focal length of the eye cannot be carried to such a stage that any object nearer than 10 inches can be sharply focused.

The adjustment by which the two eyes look at the same object is the "convergence" of the two eyes. When one is looking at a distant object the two eyes are looking straight ahead. When the object moves up to a much smaller distance one cannot still look at it with both eyes if they are looking straight ahead. They must turn in towards one another, i.e., they must converge.

Although optically these two adjustments are independent, in practice they are linked together automatically, so that when the convergence is suitable for an object distance of three feet, the accommodation is also adjusted, to ensure an object at three feet is in sharp focus. Quite a considerable effort, with resulting eye-strain, is needed in practice to break down this automatic linkage.

Now if one looks at a transparency through two lenses as shown on p. 339 the accommodation of the eye is adjusted for an object distance of from 10 inches to infinity. But the convergence is adjusted for $3\frac{1}{2}$ – $4\frac{1}{2}$ inches.

Hence to get strain-free binocular vision with a single transparency in the viewer requires a rather complicated apparatus that is hardly worth while. One very soon gets used to looking at transparencies with one eye.

A final point that should be mentioned is the question of illumination in direct vision viewers. As a rule a piece of ground glass is placed behind the transparency. This scatters light incident on it and sends it through the transparency, through the magnifying lens, and to the eye. To get the best illumination with this means pointing the viewer towards a bright light source so that the ground glass is evenly illuminated. This gives quite satisfactory results as a rule. It breaks down occasionally when a rather dense colour transparency is being examined, and in such a case an improvement can be effected by putting a condenser of about $2\frac{1}{2}$ inches focus behind the ground glass (p. 339).

There is one point, of interest rather than major importance, that may be noted in connection with the use of film readers of either type and colour film. It is the effect of the colour of the light used on the quality of the projected image. What this means in a film reader, is that if the light furnished by the lamp has a preponderance of red in its make-up, then red hues in the projected image will be emphasised. Such is the general effect obtained in all but exceptional cases. Contrasted with sunlight, or average outdoor light, the light supplied by the lamp is decidedly biased to the red end of the spectrum. Hence, assuming that the film gives an exact record of the colour distribution in the original scene taken by daylight, the projected image will be rather too red—whether this is noticeable or not depends on psychological factors. It can be remedied by putting a light blue filter between the lamp and condenser or between the condenser and the slide.

OPTICAL CALCULATIONS

The treatment of optical matters in the foregoing pages has been cast, as far as possible, in a non-mathematical form. On occasions this limits the precision and completeness with which such topics may be discussed—a valid limitation, since this book is intended for photographers and does not claim to be a text-book of optical design.

At the same time it may be of interest and value to consider a few topics in greater mathematical detail. It has been necessary to draw a line somewhere, and for this reason no account has been given of methods of calculating coma, astigmatism, distortion, or lateral chromatic aberration, etc. For further details of extra-axial calculations reference should be made to standard texts on optical design, a number of which are listed in the bibliography on p. 370.

To the non-mathematical reader: It is not at all necessary to master the contents of this chapter to understand the rest of the book. The results to which mathematical work leads have been summarised in the text in straight-forward language, and in a fashion quite independent of the treatment now given.

Calculation of Focal Length

The fundamental equation for the refraction of a light ray at the surface separating two media of refractive indices N and N^1 is

$$N \cdot \sin i = N^1 \cdot \sin i^1 \quad \dots \quad \dots \quad \dots \quad (1),$$

where i and i^1 are the angles which the ray makes with the normal to the surface at the point where it meets the surface.

Now consider a ray of light travelling from left to right, as shown in the diagram on p. 345, and encountering a refracting surface of radius r . r is reckoned as positive when it is convex towards the incident light, negative when it is concave towards the light. Before refraction the ray is directed towards a point distant l from the vertex of the refracting surface, and makes an angle u with the axis of the optical system (i.e., the line on which lie the centres of the spherical surfaces bounding the refracting materials used in the lens. Only spherical refracting surfaces will be considered). l is reckoned as positive when the point X shown in the diagram lies to the right of the vertex of the surface, and u is

reckoned as positive when the ray is sloping towards the axis as shown in the diagram. After refraction the ray is described by analogous numbers l^1 and u^1 .

It is easily seen from the diagram that the angle i between the normal (in this case the radius of the sphere through the point of intersection) and the ray, before refraction, is given by

$$\sin i = \frac{l - r}{r}. \quad \sin u \quad \dots \quad \dots \quad \dots \quad (2).$$

After refraction it is given by

$$\sin i^1 = \frac{l^1 - r}{r}. \quad \sin u^1 \quad \dots \quad \dots \quad \dots \quad (3).$$

By making use of the relation $(i + u) = (i^1 + u^1)$ it is possible to obtain the quantities relating to the ray after refraction, from those relating to the ray before refraction and the radius of the refracting surface, as well as the refractive indices across the surface. In this way a ray may be traced through a lens, provided that it lies initially in a plane through the lens axis.

A ray traced in this way shows the existence of aberrations, and in fact such ray tracing is used to determine what aberrations are present over and above the first order aberrations (see pp. 101–103). The focal length of a lens, and the properties of the nodal points are bound up with the notion of a perfect lens, i.e., one that is free from aberrations. Such a lens is a limiting case of an actual lens in the event of its field and aperture being severely restricted. From the mathematical point of view the procedure equivalent to using a lens under these conditions is to take the limiting values of sines and tangents of angles when these are small, namely to equate sines and tangents to angles in radian measure. At the same time the refracting surface is taken to deviate by only a second order amount from the tangent plane at its vertex.

Under these conditions we may change the notation somewhat, and denote the quantity formerly labelled l by s . The analogous quantity after refraction is s^1 . Denote the height above the lens axis at which the ray encounters the refracting surface as h (for this purpose the surface is taken to coincide with its vertex tangent plane), and let the distance between the r -th and $(r + 1)$ th surfaces, measured along the lens axis, be $t(r)$. Then the fundamental equations may be written :

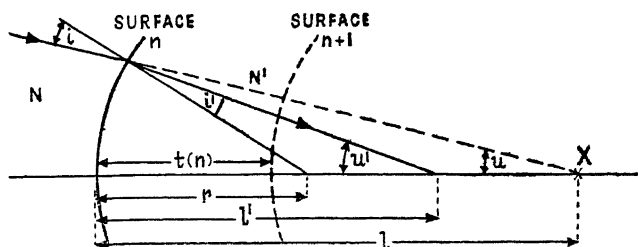
$$Q = N. \left(\frac{1}{r} - \frac{1}{s} \right) = N^1 \left(\frac{1}{r} - \frac{1}{s^1} \right). \quad \dots \quad \dots \quad (4a).$$

$$h(r + 1) = h(r). \frac{s(r + 1)}{s^1(r)}. \quad \dots \quad \dots \quad (4b).$$

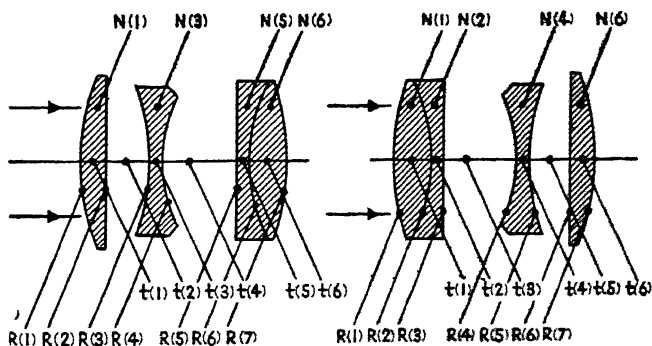
$$s(r + 1) = s^1(r) - t(r) \quad \dots \quad \dots \quad (4c).$$

By using these equations one may draw up a schedule of calculations to work out the focal length of a lens given its curve radii and other relevant data. The quantity Q defined above may be called the *Abbe invariant*.

For purposes of calculation take a nominal value of 1.000 as the value of h on the first surface, and take the value of s on the first surface as ∞ , noting that $1/\infty$ is zero. For any surface in the lens the calculations then run:



The path of a ray of light through a lens is traced by relating the distance l^1 and the angle u^1 after refraction, to the distance l and the angle u before refraction. The index of refraction is taken to be N before refraction, and N^1 after refraction. The value of u for the $(n+1)$ th surface is u^1 for the (n) th surface, and l is $l^1 - t(n)$. This gives the exact path and is free from approximations when the exact law of refraction, i.e., $N \sin i = N^1 \sin i^1$ is used (p. 344).



The diagrams show (left) a Tessar lens as it is normally used, with parallel light incident on the outside surface of the single glass, and (right) the same lens reversed so that parallel light first encounters a surface of the cemented doublet. The quantities N , R , and t that are used in calculating the focal length, as explained in the text, are shown, for the two cases of the lens the right way round and reversed back to front (pp. 346-349).

CALCULATION OF FOCAL LENGTH

1. Write down the value of the radius, taking note as explained above as to whether it is positive or negative.
2. Take $1 \div$ the radius.
3. Write down the value of s at this surface.
4. Take $1 \div s$.
5. Subtract 4. from 2.
6. Write down the value of N , i.e., the refractive index of the medium in which the ray is travelling before refraction.
7. Multiply 5. by 6. This gives the value of Q .
8. Write down the value of N^1 , i.e., the refractive index after refraction.
9. Divide 7. by 8.
10. Subtract 9. from 2.
11. Take $1 \div$ 10. This gives the value of s^1 .
12. Write down the separation between this surface and the following surface.
13. Subtract 12. from 11. This gives the value of s to be used in the calculations for the next surface at stage 3.
14. Take the value of h for the preceding surface, and multiply it by s for the current surface.
15. Divide 14. by s^1 , i.e., 11, for the preceding surface. This gives h for the current surface. When the current surface is the first the steps 13 and 14 are omitted, and the nominal value 1.000 written down for 15.

To get the focal length F of the lens divide the value of s^1 at the last surface of the lens by the value of h on that surface. The back focus of the lens is the value of s^1 at the last surface. The distance of the rear nodal point, inside the lens from the last surface, is the equivalent focal length minus the back focus.

As a check it is advisable to make a calculation with the lens turned round, so that light from infinity enters the glass that, in actual use, is at the rear of the lens. Special care must be taken in this case to note that the proper signs are given to the radii. The focal length of this reversed lens should be the same as the lens the proper way round. The difference between the equivalent focal length and the value of s^1 on the last surface, in this case, gives the position of the front nodal point, when the lens is used the right way round.

As an example the calculation of the focal length of a lens of Tessar form is given in detail on p. 347. The lens is shown in the diagram on p. 345, and has the following characteristics (note that the refractive index of air is equal to 1.000 and is not explicitly stated as a rule when the data are given, although it is used in the calculation).

LENS RIGHT WAY ROUND.

$R(1) + .3210$; $R(2) \infty^*$; $R(3) - .7110$; $R(4) + .2880$; $R(5) \infty$;
 $R(6) + .2850$; $R(7) - .4720$.
 $t(1) .046$; $t(2) .054$; $t(3) .037$; $t(4) .067$; $t(5) .015$; $t(6) .080$.
 $N(1) 1.6072$ $N(3) 1.5760$ $N(5) 1.5265$; $N(6) 1.6238$.

* ∞ means that the surface is flat.

As explained above the negative sign means that the surface is concave to the incident light, supposed travelling from left to right.

TESSAR LENS.—(RIGHT WAY ROUND)

| SURFACE | 1. | 2. | 3. | 4. | 5. | 6. | 7. | | | | | | | |
|----------|--------|--------|--------|--------|--------|--------|--------|-------|-------|-------|-------|-------|-------|-------|
| (1) ... | + | .3210 | ∞ | — | .7110 | + | .2880 | ∞ | + | .2850 | — | .4720 | | |
| (2) ... | + | 3.115 | 0.0 | — | 1.406 | + | 3.472 | 0.0 | + | 3.509 | — | 2.119 | | |
| (3) ... | ∞ | + | .8036 | + | .4460 | + | 1.063 | — | 2.001 | — | 3.068 | — | 10.38 | |
| (4) ... | 0.0 | + | 1.244 | + | 2.242 | + | .9407 | — | .500 | — | .326 | — | .096 | |
| (5) ... | + | 3.115 | — | 1.244 | — | 3.648 | + | 2.531 | + | .500 | + | 3.835 | — | 2.023 |
| (6) ... | 1.0 | 1.6072 | 1.0 | 1.5760 | 1.0 | 1.5265 | 1.6238 | | | | | | | |
| (7) ... | + | 3.115 | — | 2.000 | — | 3.648 | + | 3.989 | + | .500 | + | 5.854 | — | 3.285 |
| (8) ... | 1.6072 | 1.0 | 1.5760 | 1.0 | 1.5265 | 1.6238 | 1.0 | | | | | | | |
| (9) ... | + | 1.938 | — | 2.000 | — | 2.315 | + | 3.989 | + | .328 | + | 3.606 | — | 3.285 |
| (10) ... | + | 1.177 | + | 2.000 | + | .909 | — | .517 | — | .328 | — | .097 | + | 1.166 |
| (11) ... | + | .8496 | + | .5000 | + | 1.100 | — | 1.934 | — | 3.053 | — | 10.30 | + | .8574 |
| (12) ... | .046 | .054 | .037 | .067 | .015 | .080 | | | | | | | | |
| (13) ... | + | .8036 | + | .4460 | 1.063 | — | 2.001 | — | 3.068 | — | 10.38 | | | |
| (14) ... | | + | .8036 | + | .4219 | + | .8968 | — | 1.632 | — | 2.588 | — | 8.799 | |
| (15) ... | 1.000 | .9459 | .8437 | .8155 | .8438 | .8477 | .8541 | | | | | | | |

The equivalent focus of the lens is $.8574 \div .8541 = 1.004$ inches ; the back focus is .8574 inch ; and the rear nodal point is inside the lens, a distance $1.004 - .857 = .147$ inch from the back glass.

For purposes of subsequent calculation it will be sufficiently accurate to take the equivalent focal length of this lens as 1.000 inch.

TESSAR LENS.—(REVERSED BACK TO FRONT)

| SURFACE | 1. | 2. | 3. | 4. | 5. | 6. | 7. |
|----------|---------|---------|---------|---------|---------|---------|---------|
| (1) ... | + .4720 | - .2850 | ∞ | - .2880 | + .7110 | ∞ | - .3210 |
| (2) ... | + 2.119 | - 3.509 | 0.0 | - 3.472 | + 1.406 | 0 | - 3.115 |
| (3) ... | ∞ | + 1.149 | + .855 | + .493 | + 55.51 | - 1.333 | - 2.188 |
| (4) ... | 0 | + .871 | + 1.170 | + 2.028 | + .018 | - .750 | - .457 |
| (5) ... | + 2.119 | - 4.380 | - 1.170 | - 5.500 | + 1.388 | + .750 | - 2.658 |
| (6) ... | 1.0 | 1.6238 | 1.5265 | 1.0 | 1.5760 | 1.0 | 1.6072 |
| (7) ... | + 2.119 | - 7.112 | - 1.785 | - 5.500 | + 2.188 | + .750 | - 4.270 |
| (8) ... | 1.6238 | 1.5265 | 1.0 | 1.5760 | 1.0 | 1.6072 | 1.0 |
| (9) ... | + 1.305 | - 4.659 | - 1.785 | - 3.490 | + 2.188 | + .467 | - 4.270 |
| (10) ... | + .814 | + 1.150 | + 1.785 | + .018 | - .782 | - .467 | + 1.155 |
| (11) ... | + 1.229 | + .870 | + .560 | + 55.55 | - 1.279 | - 2.142 | + .8678 |
| (12) ... | .080 | .015 | .067 | .037 | .054 | .046 | |
| (13) ... | + 1.149 | + .855 | + .493 | + 55.51 | - 1.333 | - 2.188 | |
| (14) ... | | + 1.149 | + .7998 | + .4531 | + 44.92 | - 1.078 | - 1.845 |
| (15) ... | 1.000 | .9353 | .9193 | .8092 | .8086 | .8430 | .8612 |

The equivalent focal length is $.8678 \div .8612 = 1.007$ inches ; the back focus of the reversed lens is .8678 or .868 inch ; and the nodal point, i.e., the front nodal point when the lens is the right way round, is $1.008 - .868 = .140$ inch behind the front glass.

LENS REVERSED

When the lens is turned round the formula for it becomes :

$$\begin{aligned} R(1) + .4720 ; R(2) - .2850 ; R(3) \infty ; R(4) - .2880 ; R(5) + .7110 ; \\ R(6) \infty ; R(7) - .3210. \\ t(1) .080 ; t(2) .015 ; t(3) .067 ; t(4) .037 ; t(5) .054 ; t(6) .046. \\ N(1) 1.6238 ; N(2) 1.5265 ; \quad N(4) 1.5760 ; \quad N(6) 1.6072. \end{aligned}$$

The calculation scheme just given is not as elegant as some that have been proposed, but it is of considerable practical use, and by using a suitable slide rule (for instance one of the *Otis King* pattern), or 4-figure logarithms, the focal length of the average lens may be quickly worked out with an accuracy of about $\frac{1}{2}\%$.

The values obtained for the focal lengths, 1.004 inches and 1.007 inches are in sufficiently close agreement for slide rule work.

Axial Chromatic Aberration

The theory of chromatic aberration as given in standard texts, as a rule, is applicable only to the case of two thin lenses in contact. Such a pair form, for example, a rather idealised telescope objective. The condition for achromatism in the case of a thin lens, namely

$$\frac{1}{V} \cdot \frac{1}{F} + \frac{1}{V_1} \cdot \frac{1}{F_1} = 0 \quad \dots \quad (5).$$

means that not only are all rays brought to the same focus (to a first approximation, neglecting secondary spectrum) but also that the focal length is the same for all colours. In dealing with photographic lenses this thin lens theory is not sufficiently accurate.

In correcting axial chromatic aberration in a photographic lens the first aim is to bring all rays to a focus in the same point, for a given position of the object point, usually when this is at infinity (again we are neglecting secondary spectrum for the time being). The formulæ and the computing scheme are then as follows :

Carry through the calculation given for determining the focal length on pp. 346-347, or an analogous calculation with a required value of s on the first surface, if the lens is not to be used at infinity but with an object point at a finite distance. Note the value of Q and h on each surface. The calculation is carried out in the vast majority of cases with the refractive index of the material corresponding to sodium or helium yellow. If nothing is stated to the contrary this may quite safely be assumed. Now suppose that the refractive index of the material in which a ray is travelling before refraction at a given surface has a value N for sodium yellow, N_c for hydrogen red, and N_r for hydrogen blue light, then it has an Abbe number V given by

$$V = \frac{N - 1}{N_r - N_c} \quad \dots \quad (6).$$

In the same way the material in which the ray is travelling after refraction has an Abbe number V^1 .

Now form the quantities w and w^1 defined by

$$w = \frac{N-1}{N} \cdot \frac{1}{V}, \quad w^1 = \frac{N^1-1}{N^1} \cdot \frac{1}{V^1} \dots \dots (7).$$

and the differences $w^1 - w$ for each surface. Note that when the material in which the ray is travelling is air, then $w = 0$. Write d for $w^1 - w$.

At each surface form the product $Q \times h^2 \times d$, call it k . Add up all the k 's so obtained, taking due note of the sign of each, and denote the sum by K . The condition that hydrogen red and hydrogen blue light should come to the same focus, with a given position of the object point, for which the calculation of the Q 's and h 's has been carried out, is that K should be zero.

The calculation of the K 's for the Tessar lens described on p. 342, and for which the calculation of the Q 's, etc. has been carried out for the lens the right way round and reversed, is given below assuming that with the lens the right way round the glasses have V 's and w 's.

$$\begin{aligned} V(1) \ 59.5; \quad V(3) \ 41.3; \quad V(5) \ 51.4; \quad V(6) \ 56.9 \\ w(1) \ .00635; \quad w(3) \ .00885; \quad w(5) \ .00671; \quad w(6) \ .00675 \end{aligned}$$

and with the lens reversed

$$\begin{aligned} V(1) \ 56.9; \quad V(2) \ 51.4; \quad V(4) \ 41.3; \quad V(6) \ 59.5 \\ w(1) \ .00675; \quad w(2) \ .00671; \quad w(4) \ .00885; \quad w(6) \ .00635. \end{aligned}$$

TESSAR LENS.—(RIGHT WAY ROUND)

| SURFACE | 1. | 2. | 3. | 4. | 5. | 6. | 7. | | | | | |
|---------------------|--------|--------|---------|--------|--------|--------|--------|--------|---------|---|--------|---------|
| Q ... | +3.115 | -2.000 | -3.648 | +3.989 | + | .500 | +5.854 | -3.285 | | | | |
| h ... | 1.000 | .9459 | .8437 | .8155 | | .8438 | .8477 | .8541 | | | | |
| Q × h ² | +3.115 | -1.788 | -2.597 | +2.654 | + | .356 | +4.208 | -2.396 | | | | |
| w ... | 0.0 | .00635 | 0.0 | .00885 | 0.0 | | .00671 | .00675 | | | | |
| w ^I ... | | .00635 | 0.0 | .00885 | 0.0 | .00671 | .00675 | 0.0 | | | | |
| d ... | + | .00635 | -.00635 | + | .00885 | + | .00671 | .00004 | -.00675 | | | |
| Qh ² × d | + | .01977 | +.01136 | - | .02298 | - | .02348 | + | .00239 | + | .00017 | +.01617 |

The sum of all the quantities k ($k = Q \times h^2 \times d$) is +.00340. This is the quantity denoted by K in the text.

TESSAR LENS.—(REVERSED, BACK TO FRONT)

| SURFACE | 1. | 2. | 3. | 4. | 5. | 6. | 7. |
|---------------------|----------|----------|----------|----------|----------|----------|----------|
| Q ... | + 2.119 | - 7.112 | - 1.785 | - 5.500 | + 2.188 | + .750 | - 4.270 |
| h ... | 1.000 | .9353 | .9193 | .8092 | .8086 | .8430 | .8612 |
| Q x h ² | + 2.119 | - 6.225 | - 1.510 | - 3.598 | + 1.429 | + .533 | - 3.165 |
| w ... | 0.0 | .00675 | .00671 | 0.0 | .00885 | 0.0 | .00635 |
| w ¹ ... | .00675 | .00671 | 0.0 | .00885 | 0.0 | .00635 | 0.0 |
| d ... | .00675 | - .00004 | - .00671 | + .00885 | - .00885 | + .00635 | - .00635 |
| Qh ² x d | + .01430 | + .00025 | + .01013 | - .03185 | - .01264 | + .00338 | + .02010 |

The sum of all the quantities k is +.00367 = K .

It is of particular interest to examine the consequences of K not being equal to zero. If K is positive the hydrogen blue light comes to a focus nearer the lens than the hydrogen red light, and the lens is *under-correct* for axial chromatic aberration. If K is negative the position is reversed and the lens is *over-correct*. In each case the separation between the foci for hydrogen blue and red light is given by the formula

$$\text{Separation} = K \div (\text{focal length})^2 \quad \dots \quad (8).$$

Thus in the example of the Tessar given we have in each case, for the lens the right way round and for the lens reversed, a focal length of 1.000, and the square of the focal length is also 1.000. Hence the separation between the red and blue foci is equal to the values of K given, namely with the lens the right way round the separation is .0034 inch, and the blue is nearer the lens, while when the lens is turned round the separation is .0037 inch and the blue is again nearer the lens.

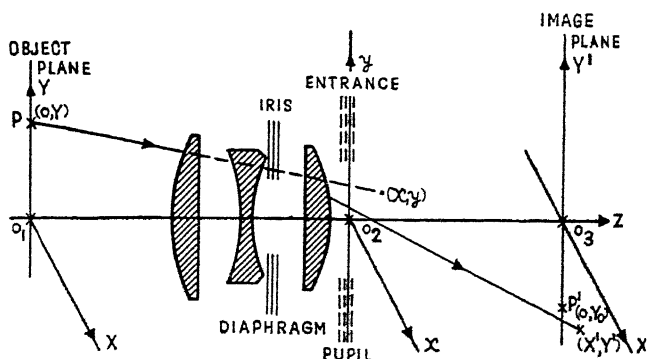
If the refractive index of any of the glasses used be N_e for light of a colour other than hydrogen red or blue, we can calculate a V_o and w_o for hydrogen red and this colour. The condition then that all light should come to the common focus of the blue and red light, supposing that K is zero, is that the new V_o divided by the old V should be constant for every glass used in the lens. This cannot be realised with existing glasses. The differential bending for blue and red light, the dispersion of the glass, is greater for flint glasses and increases at a disproportionate rate for these glasses as the blue end of the spectrum is reached, compared with the rate of increase for the crown glass or barium flint types that are used for the converging elements in the composite lens. Hence there is introduced the secondary spectrum.

When the light of a particular colour A does not come to the same focus as light of another colour B , then in the absence of aberrations and supposing that the second light B comes to a focus on the sensitive material, there is produced a disc of light of the colour A , whose diameter varies directly as the aperture of the lens.

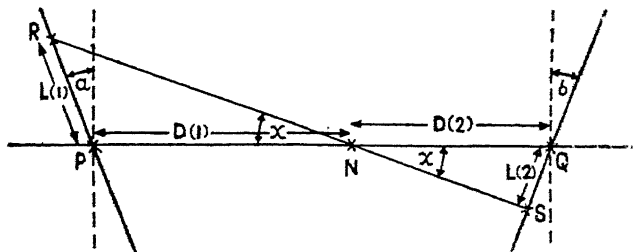
Aberrations in General

Take the z -axis of a rectangular co-ordinate system along the lens axis as shown in the diagram p. 351. Take the y -axis of co-ordinates through the object point P , and the x -axis at right angles to the other two axes. Then the position of the object point in the object plane through P at right angles to the lens axis, has co-ordinates (O, Y) . If we then consider the point in which a light ray starting from P cuts the corresponding image plane (defined on the assumption that the lens is perfect), such a point may be defined by the co-ordinates (X^1, Y^1) . If the lens were perfect any ray would meet the image plane in the point (O, Y_o) . The deviation of the intersection point from its ideal position is due to the aberrations present.

To define more precisely the ray from the point P that is under consideration the following method is adopted: Form the image of the iris diaphragm of the lens by all the refracting surfaces that lie between it and the object plane. In the case of photographic lenses this is a virtual image, as shown in the diagram, but this is not a factor of any



A ray of light may be specified, for the purposes of analytical treatment and the development of the Seidel aberrations, by specifying the co-ordinates (o, Y) of an object point, the co-ordinates (x, y) of the point in which it meets the entrance pupil of the lens (i.e. the image, which may be virtual as here shown, of the iris diaphragm or stop in all the surfaces between it and the object). The presence of aberrations is shown by the deviation of the emergent ray's point of encounter with the image plane, having co-ordinates (X', Y') in this plane, from the ideal image position at (O, Y_0) (p. 350).



The correction of distortion in enlargers is geometrically equivalent to dealing with the projection of a plane figure, such as PR , lying in a plane making an angle of $(90 + \alpha)$ with a line PQ , upon a second plane making an angle of $(90 - b)$ with PQ , the projection being a central projection through a point N lying on PQ . The production of the distorted figure in taking the picture is a special case of this in which b is zero. In the treatment given in the text it is assumed that PNQ during enlarging coincides with NQ during taking, so defining PNQ in the enlarging stage. Normally it may be assumed that PNQ coincides with the axis of the enlarger, but by using a tilting lens or the Charles method, this condition is departed from (p. 358).

ANALYSING ABERRATIONS AND CORRECTING DISTORTION

importance. Let the co-ordinates of any point in the plane of this image be (x, y) . The image of the iris diaphragm (i.e., the aperture stop of the lens) is the *entrance pupil*. Only those rays may go through the lens, that cut the plane of the entrance pupil in the region bounded by the image of the iris. Any ray from the point P is completely defined by stating the point (x, y) in the plane of the entrance pupil through which it goes.

Then for the point in which a ray encounters the ideal image plane we can write

$$X^1 = -\frac{1}{2}x \cdot (x^2 + y^2) \cdot A + xy \cdot Y_0 \cdot B - \frac{1}{2} \cdot x \cdot Y_0^2 \cdot (C + D) \dots \\ + \text{higher powers.}$$

$$Y^1 - Y_0 = -\frac{1}{2}y \cdot (x^2 + y^2) \cdot A + (x^2 + 3y^2) \cdot Y_0 \cdot B - \frac{1}{2} \cdot y \cdot Y_0^2 \cdot \\ (3C + D) + \frac{1}{2} \cdot Y_0^2 \cdot E \dots + \text{higher powers.} \quad \dots (9).$$

The constant A represents the first order spherical aberration.

| | | | | | | | | |
|---|---|-----|---|---|---|---|---|-------------------------|
| " | " | B | " | " | " | " | " | coma. |
| " | " | C | " | " | " | " | " | astigmatism. |
| " | " | D | " | " | " | " | " | field curvature. |
| " | " | E | " | " | " | " | " | first order distortion. |

The terms with higher powers of Y , x , and y represent the effects of the higher order aberrations. It is not often a profitable proposition to calculate them in detail. A certain amount of general sorting into types is, however, possible. Thus those terms which do not involve Y_0 are classed together as spherical aberration, or as axial spherical aberration to distinguish it from oblique spherical aberration: if we concentrate attention on an object point on the lens axis these are the only terms which enter into the equations (9) expressing the effects of the aberrations. Those terms which involve powers of Y only, represent a displacement of the image from its ideal position without specifying anything about its quality: they constitute the distortion. In a photographic lens only the first order distortion is of importance, in the majority of cases. Those terms which do not involve powers of x and y higher than the first constitute the higher order astigmatism terms: they represent the light distribution due to narrow bundles of light rays through the central region of the entrance pupil.

If we concentrate attention on the first order aberrations there are a number of useful conclusions that we may give, relating to the variation of the light patches as the lens is stopped down.

1. SPHERICAL ABERRATION. If spherical aberration alone is present in a lens, A is the only non-zero constant. The rays through an annulus of the entrance pupil give a ring of light in the image plane. The light patch is built up from contiguous light rings of this type. The radius of the light ring, corresponding to a zone of the entrance pupil, varies as the cube of the radius of the zone. Hence the diameter of the light patch varies as the cube of the iris diameter, and stopping the lens down by one stop, i.e., reducing the iris diameter in the ratio $1 \div 1.4$, reduces the diameter of the light patch in the ratio $1 \div 2.8$. It is of importance to note that this only holds when the effects of higher order spherical

aberration are negligible. For photographic lenses this may be taken as implying that the rule holds fairly well for a lens stopped down by more than two stops from its maximum aperture.

ii. **COMA.** The rays of light through an annulus of the entrance pupil when coma is the only aberration present, namely when B is the only non-zero coefficient, form a ring of light in the image plane, whose centre is displaced from the ideal image position through a distance equal to the diameter of the ring. The effect of the overlapping rings, from the zones that fill the lens aperture, is to produce the typical flaring coma shape. The diameter of a ring of light varies as the square of the radius of the zone of the entrance pupil, through which the light has come, and varies directly as the distance of the ideal image position from the lens axis. Stopping down the lens by one stop means that the light patch is reduced to one half its previous size. Again these conclusions hold only when the higher order terms that are not classed under higher order spherical aberration or astigmatism (they are usually classed as higher order coma or oblique spherical aberration) contribute negligible effects. And again this holds only for a photographic lens when it is stopped down.

iii. **FIELD CURVATURE.** When D is the only non-zero co-efficient in the equations (9) the lens suffers from *field curvature*. The patch of light in the image plane is circular, and concentric with the ideal image position. Its diameter varies directly as the aperture of the lens, and as the square of the distance of the image position from the lens axis. Reducing the lens aperture by one stop reduces the diameter of the light patch to $1 \div 1.4$ of its previous size. D is closely related to the *Petzval sum* P of the lens, a quantity of particular importance. The exact relation is that $D = P \div F$ where F is the focal length of the lens. P is particularly easy to calculate, as it depends only on the glasses used in the lens and their radii, and not on their spacing and thicknesses, nor on the relative positions of object and image. Its value is obtained in this way: At each surface form the quantities u and u^1 , where $u = (N - 1) \div N$, and $u^1 = (N^1 - 1) \div N^1$, and denote by v the difference $u^1 - u$. Note that the sign of v depends on the way in which light is supposed to travel through the lens, say from left to right. With this in mind to determine the sign of $1/r$, form the product $v \times 1/r$, and call this p . Add together the contributions p from all the surfaces in the lens, taking due note of the sign of each. Then the sum P is the Petzval sum. The calculation of P for the Tessar lens already discussed is given below.

When P , and hence E , is zero the patch shrinks to a point. When P is positive it will be found that the patch of light shrinks to a point if the surface on which it is received is moved nearer the lens. The distance varies as the square of the distance of the image position from the lens axis. Hence the locus on which lie sharp image points corresponding to object points in the field of the lens is a paraboloid of revolution, or with sufficient accuracy the cap of a sphere, concave to the lens. In this event there is *under-correct field curvature*. When P is negative the surface is convex to the lens, and the field curvature is *over-correct*.

TESSAR LENS

| SURFACE | | 1. | 2. | 3. | 4. | 5. | 6. | 7. |
|----------------|-----|---------|---------|---------|---------|---------|---------|---------|
| N | ... | 1.0 | 1.6072 | 1.0 | 1.5760 | 1.0 | 1.5265 | 1.6238 |
| u | ... | 0.0 | .3775 | 0.0 | .3655 | 0.0 | .3450 | .3840 |
| N ² | ... | 1.6072 | 1.0 | 1.5760 | 1.0 | 1.5265 | 1.6238 | 1.0 |
| u ² | ... | .3775 | 0.0 | .3655 | 0.0 | .3450 | .3840 | 0.0 |
| v | ... | + .3775 | - .3775 | + .3655 | - .3655 | + .3450 | + .0390 | - .3840 |
| 1/r | ... | + 3.115 | 0.0 | - 1.406 | + 3.472 | 0.0 | + 3.509 | - 2.119 |
| p | ... | + 1.176 | 0.0 | - .514 | - 1.269 | 0.0 | + .137 | + .814 |

P , the sum of the quantities p is equal to + .344.

Note that although the calculation has been made with the lens the right way round, the same value, with the same sign, is obtained with the lens reversed.

iv. **ASTIGMATISM.** When C is the only non-zero co-efficient the image patch is an ellipse with the lengths of its axes in the ratio 3 : 1. The size of the ellipse varies as the lens aperture and as the square of the distance of the image point from the lens axis. The variation is in fact identical with that for the case of field curvature. If the surface on which the image is received is moved towards the lens, when C is positive, a position is reached when the image patch becomes a thin line along the y -axis of co-ordinates. On moving it from the ideal image plane through a distance three times as great the patch becomes a short line parallel to the x -axis. Each of these displacements varies as the square of the distance of the ideal image position from the lens axis. Thus we have two surfaces on which lie the *astigmatic lines* corresponding to object points in the field of the lens, each part of a sphere. When C is positive both surfaces are concave towards the lens ; when C is negative both surfaces are convex towards the lens.

Special interest attaches to cases where both C and D are non-zero.

(a) When $C + D = 0$ the image patch becomes a short line along the y -axis, and the surface on which lies such an astigmatic line, the *sagittal surface*, is flat. The surface on which lies the other astigmatic line, parallel to the x -axis, the *tangential surface*, is curved in a direction depending on the sign of P , since $3C + D = -2P$ in this case. With ordinary photographic lenses, other than telephotos, P is positive and the tangential surface, in these circumstances, is convex towards the lens.

(b) Of greater practical importance is the case where $3C + D = 0$. When this is so the image patch becomes a straight line parallel to the x -axis, and the tangential field is flat.

(c) Still another possibility of interest is to make $C + D = -(3C + D)$. In this event the light patch in the theoretical or ideal image plane is circular, and the surfaces in which lie the sagittal and tangential astigmatic lines are equally curved, one concave to the lens, the other convex towards it.

If one considers the first order astigmatism and field curvature only it is evident that a flat field can be obtained when both C and D (and hence P) are zero together. When a field of any great extent is to be covered the first order theory is not of itself adequate to represent the lens performance. Higher order astigmatism terms have to be taken into account to describe the departure of the astigmatic surfaces from their simple first order form. In these circumstances it is not always advisable to make the Petzval sum too small: it must be chosen to give the best balance of first and higher order astigmatism over the whole field.

v. **DISTORTION.** When E is the only non-zero co-efficient the sole image defect is that it is displaced from its ideal position, by an amount that varies as the cube of the distance of the image point from the lens axis. It does not depend on the lens aperture and hence is not affected by stopping down the lens. The variation as the cube of the distance is responsible for the typical pin-cushion and barrel distortion shapes. Higher order distortion in photographic lenses is of importance only in survey lenses.

Although the aberration formulæ, as given in equations (9), do not show it explicitly, it must be borne in mind that the values of the co-efficients A to E depend on the positions of the object and image relative to the lens.

In any actual lens it is essential to balance aberrations to give the best possible definition over the whole area of the plate or film. With the present-day state of the mathematical theory underlying lens design, the design of a photographic lens is more an art than a science.

Calculation of Spherical Aberration

It is not possible within the compass of this book to discuss the calculation of off-axis aberrations, and the balancing of aberrations over the field covered. The case of spherical aberration is however much simpler, and merits further consideration.

It has been pointed out in the previous section that, in the presence of first order spherical aberration, an image patch is produced whose diameter varies as the cube of the lens aperture. This may be put in a slightly different form: In the presence of first order spherical aberration rays of light through zones of the aperture, or entrance pupil, come to either progressively longer or shorter foci as the radii of the zones are increased. The distance between the point where rays meet, that come through a particular zone, and the point where the rays meet that come through the central zones of the lens aperture, varies as the square of the zone radius.

A constant defining the amount of this deviation, and one that is closely related to the co-efficient A of the previous section, may be calculated in this way: Calculate the values of Q and h for each surface, as explained on p. 344, using the initial value of s corresponding to the distance of the object point in front of the lens. For normal taking lenses the calculation is carried out with the object point at infinity, and this will be assumed in working out the examples given below. At each surface form the quantities q and q^1 , where $q = (1/s) \div N$,

and $q^1 = (l/s^1) \div N^1$. Denote by d the value of $q - q^1$. At each surface form the quantity g , where

$$g = (Qh^2)^2 \times d \quad \dots \quad \dots \quad \dots \quad (10).$$

Add together the values of g contributed by all the surfaces in the lens, and denote their sum by G .

If G is negative, the lens is *under-correct* for spherical aberration, and rays through successive zones of the aperture come to progressively shorter foci. When G is positive the lens is *over-correct* and rays go to progressively longer foci. In either event the distance from the central focus of rays through the margin of the lens, i.e., those whose passage is just permitted by the Iris diaphragm, is equal to the value of G multiplied by the fourth power of the focal length, divided by eight times The square of the f /number at which the lens is working.

TESSAR LENS.—(RIGHT WAY ROUND)

| SURFACE | 1. | 2. | 3. | 4. | 5. | 6. | 7. |
|-------------------------------------|-------------|---------|----------|---------|--------|---------|---------|
| Q | ... + 3.115 | - 2.000 | - 3.648 | + 3.989 | + .500 | + 5.854 | - 3.285 |
| h | ... 1.000 | .9459 | .8437 | .8155 | .8438 | .8477 | .8541 |
| Qh ² | ... + 3.115 | - 1.788 | - 2.597 | + 2.654 | + .356 | + 4.208 | - 2.396 |
| (Qh ²) ² ... | + 9.705 | + 3.198 | + 6.745 | + 7.045 | + .127 | + 17.70 | + 5.738 |
| l/s | ... 0.0 | + 1.244 | + 2.242 | + .941 | - .500 | - .326 | - .096 |
| N | ... 1.0 | 1.6072 | 1.0 | 1.5760 | 1.0 | 1.5265 | 1.6238 |
| q | ... 0.0 | + .774 | + 2.242 | + .597 | - .500 | - .214 | - .059 |
| l/s ³ | ... + 1.177 | + 2.000 | + .909 | - .517 | - .328 | - .097 | + 1.166 |
| N ³ | ... 1.6072 | 1.0 | 1.5760 | 1.0 | 1.5265 | 1.6238 | 1.0 |
| q ³ | ... + .732 | + 2.000 | + .577 | - .517 | - .215 | - .060 | + 1.166 |
| d | ... - .732 | - 1.226 | + 1.665 | + 1.114 | - .285 | - .154 | - 1.225 |
| g | ... - 7.105 | - 3.920 | + 11.240 | + 7.850 | - .036 | - 2.725 | - 7.020 |

G , the sum of the g 's is equal to -1.716 . Note that the value of G is less than most of the individual contributions g , and that its value is due to a balancing of these individual terms. Since the Q 's, h 's etc., depend on the initial value of s on the first surface, the value of G will depend on the positions of the object and image relative to the lens.

The lens in question has a focal length of 1.000 inch. The fourth power of 1.000 is equal to 1.000. If it is used at $f/4.5$, then 4.5 squared is equal to 20.25. Eight times 4.5 squared is 162. Hence, according to the formula given in the text, if the effects of higher order aberrations are negligible, the marginal rays focus nearer the lens than the central rays, by a distance $1.716 \div 162 = .0106$ inch. In a similar way the rays through the $f/6.3$ zone also focus nearer the lens than the central or paraxial rays, the distance between them being .0053 inch.

TESSAR LENS.—(REVERSED, BACK TO FRONT)

| SURFACE | 1. | 2. | 3. | 4. | 5. | 6. | 7. |
|-------------------------------------|---------|---------|---------|----------|---------|--------|----------|
| Q ... | + 2.119 | - 7.112 | 1.785 | - 5.550 | + 2.188 | + .750 | - 4.270 |
| h ... | 1.000 | .9353 | .9193 | .8092 | .8086 | .8430 | .8612 |
| Qh ² ... | + 2.119 | - 6.225 | - 1.510 | - 3.598 | + 1.429 | + .533 | - 3.165 |
| (Qh ²) ² ... | + 4.492 | + 3.872 | + 2.278 | + 12.96 | + 2.042 | + .284 | + 10.02 |
| I/s ... | 0.0 | + .871 | + 1.170 | + 2.028 | + .018 | - .750 | - .457 |
| N ... | 1.0 | 1.6238 | 1.5265 | 1.0 | 1.5760 | 1.0 | 1.6072 |
| q ... | 0.0 | + .537 | + .766 | + 2.028 | + .011 | - .750 | - .284 |
| I/s ³ ... | + .814 | + 1.150 | + 1.785 | + .018 | - .782 | - .467 | + 1.155 |
| N ³ ... | 1.6238 | 1.5265 | 1.0 | 1.5760 | 1.0 | 1.6072 | 1.0 |
| q ³ ... | + .501 | + .753 | + 1.785 | + .011 | - .782 | - .291 | + 1.155 |
| d ... | - .501 | - .216 | 1.019 | + 2.017 | + .793 | - .459 | - 1.439 |
| g ... | - 2.250 | - 8.360 | - 2.323 | + 26.130 | + 1.620 | - .130 | - 14.410 |

G, the sum of the g's for the lens used the wrong way round, is thus + .277. Note that by comparison with the lens the right way round, this new setting shows over-correct first order spherical aberration. Since higher order of spherical aberration also introduces over-correction, there is produced an unfavourable light distribution and the central definition is soft. Such a variation has a bearing on the use of the lens in an enlarger. It is not as a rule necessary to carry through the spherical aberration calculation with the lens turned round.

The next order of spherical aberration may be calculated in a rather longer manner. As a rule, however, in order to balance the over-correction that is normally introduced when the first order spherical aberration is approximately corrected, the amount of spherical aberration is not calculated order by order. Rays are traced through the lens using the formulæ given on p. 344, so that one ray passes through the margin of the lens aperture, and the other goes through a zone of the aperture having a radius .7 of that through which goes the marginal ray. One convenient practice, when a lens is being designed, is to calculate the first order aberration for some particular form of the lens, and then calculate the positions in which the marginal and .7 zone rays cut the lens axis. A change in the first order aberration is then made, by varying the shapes of the individual lenses without affecting their powers, i.e., by "bending" the lenses. Such a change, in the absence of higher order aberration, would move the marginal ray through a required distance. The zonal and marginal rays are then traced again to act as a check. When the under-correction of the zonal ray, and the over-correction of the marginal ray, are excessive for a particular lens type, a rather complicated procedure must be followed to get them within reasonable bounds, if indeed this should prove possible.

One point of importance is that both the first and higher order spherical aberration depend on the colour of the light, since they depend on the refractive indices of the glasses, which in turn depend on the colour or wavelength of the light used. The general tendency is towards over-correction of spherical aberration for blue light when the correction is established for green or yellow light. For this reason

K of p. 349 is usually left slightly positive, so that the chromatic under-correction so introduced helps to compensate the over-correct spherical aberration.

Correction of Distortion

The general ideas connected with the correction of distortion in enlargers have been discussed on pp. 317-328. What is considered here are the mathematical arguments leading to the results there quoted. It should be pointed out that the treatment now given is that which may be of value to normal photography, and not to the rectification of such things as aerial photographs where the problems to be solved are posed in somewhat more general terms.

Since the correction of distortion is considered for cases where the definition is not perfectly sharp, it is necessary to establish conventionally what we mean by the position of an un-sharp image. The convention now adopted differs from that defined on p. 120, and is this: From an object point, which may be on the negative to be enlarged, a line is drawn to the nodal point of the lens used. This defines one light ray. To it there corresponds a second, issuing from the other nodal point in a direction parallel to the first. The position of the image point or patch is the point in which this second ray or line cuts the image plane or enlarging board. The separation of the nodal points is not a factor of importance. To all intents we can consider the path of the ray as comprising two discrete parts, the first joining the object point to the first nodal point, and the second joining the image point to the second nodal point. Exactly the same image pattern is obtained if we neglect the nodal point separation and consider the image as the central projection of the object, with the joint nodal point, *N* in the diagram on p. 351, as the centre of projection.

Consider two planes through points *P* and *Q*, inclined at angles *a* and *b* to their square-on position as shown. The line *PNQ* may be, for instance, the axis of a lens. Then we have to consider two ratios. The first is the ratio of the two lengths *PR* and *QS*, call it *M*(1). The second is the ratio of the lengths of two lines through *R* and *S* at right angles to the plane of the paper, call it *M*(2). Denote by *x* the angle between *RNS* and *PNQ*, by *D*(1) the distance *PN*, and by *D*(2) the distance *NQ*. Call *PR* *L*(1), and *QS* *L*(2).

$$\text{Then } \frac{L(1)}{\sin x} = \frac{D(1)}{\cos(a+x)} \dots \dots \dots (11).$$

Hence

$$\tan x = (L(1) \cdot \cos a) \div (D(1) + L(1) \cdot \sin a) \dots \dots (12a).$$

Similarly

$$\tan x = (L(2) \cdot \cos b) \div (D(2) - L(2) \cdot \sin b) \dots \dots (12b).$$

Eliminating $\tan x$ from these equations gives the result

$$L(2) = L(1) \cdot D(2) \cdot \cos a \div (D(1) \cdot \cos b + L(1) \sin(a+b)) \dots (13).$$

Now in taking a photograph with the camera tilted at an angle *t* to the horizontal, we have to put *b* = 0 and *a* = *t*. In this instance denote

the dimensions previously represented by capitals, by lower case symbols. The numeral (1) refers to a vertical object being photographed and its distance from the lens nodal point, while (2) refers to its image on the sensitive material, and the distance of this from the nodal point. Then $l(2) = l(1) \cdot d(2) \cdot \cos t \div (d(1) + l(1) \cdot \sin t) \dots \dots (14)$. If now this negative is placed in an enlarger in which (1) refers to the negative and its slope, etc., while (2) refers to the enlarging board, we have to substitute the value of $l(2)$ from (14) for $L(1)$ in (13). This gives

$$L(2) = D(2) \cdot \cos a \cdot l(1) \cdot d(2) \cdot \cos t \div (C + l(1) \cdot d(2) \cdot \cos t \cdot \sin(a + b)) \dots \dots (15)$$

where

$$C = D(1) \cdot \cos b \cdot (d(1) + l(1) \cdot \sin t).$$

Reverting to the magnifications $M(1)$ and $M(2)$ we can write

$$\begin{aligned} M(1) &= L(2) \div L(1) \\ M(2) &= NS \div NR = M(1) \cdot \cos b \div \cos a \dots \dots (16) \end{aligned}$$

Hence, if in the enlargement the distortion is to be removed, it is necessary that the denominator in (15) should be independent of $l(1)$, i.e., the co-efficient of $l(1)$ in the denominator must be zero.

Thus the condition for parallelism of perpendiculars is

$$\sin t \cdot D(1) \cdot \cos b + d(2) \cdot \cos t \cdot \sin(a + b) = 0$$

or neglecting sign

$$\tan t = \frac{d(2)}{D(1)} \cdot \frac{\sin(a + b)}{\cos b} \dots \dots (17)$$

When this relation is established we have from (15)

$$L(2) = l(1) \cdot \frac{d(2)}{d(1)} \cdot \frac{D(2)}{D(1)} \cdot \frac{\cos a \cdot \cos t}{\cos b} \dots \dots (18)$$

Since there is now no convergence in the negative, we can write

$$M(2) = \frac{D(2)}{D(1)} \cdot m(2) = \frac{d(2)}{d(1)}$$

and if we put $L(2) \div l(1) = M(1) \cdot m(1)$, since $L(1) = l(2)$, we have

$$M(1) \cdot m(1) = M(2) \cdot m(2) \cdot \frac{\cos a \cdot \cos t}{\cos b} \dots \dots (19)$$

The overall magnifications in the two directions at right angles differ by the factor involving the cosines. If there is to be no elongation then

$$\frac{\cos a \cdot \cos t}{\cos b} = 1 \dots \dots (20)$$

Similar formulæ may be worked out for the case of a tilted camera back. They differ only in detail.

In general the camera lens is focused on infinity and we can put $d(2) = f$, where f is the focal length of the taking lens.

If the negative is to be sharp all over we have the additional conditions to satisfy, that

$$D(1) = \frac{M + 1}{M} \cdot F; D(2) = (M + 1) \cdot F; \text{ and } \tan b = M \tan a \quad (21)$$

If in general we write $D(2) \div D(1) = M$, then we can summarise the conditions to be satisfied as :

$$\text{Parallelism : } \tan t = \frac{f}{D(1)} \cdot \frac{\sin(a+b)}{\cos b} \quad \dots \quad \dots \quad \dots \quad (22a).$$

$$\text{Proportionality : } \cos a \cdot \cos t = \cos b \quad \dots \quad \dots \quad \dots \quad (22b).$$

$$\text{Definition : } \tan b = M \cdot \tan a \text{ and } D(1) = \frac{M+1}{M} \cdot F \quad \dots \quad (22c).$$

$$\text{Magnification : } D(2) = M \times D(1) \quad \dots \quad \dots \quad \dots \quad (22d).$$

These equations bring out some points of interest.

In the first place (22d), is not of particular importance. It does not constitute a limitation since the other equations do not depend on $D(2)$, and $D(2)$ can be adjusted to satisfy (22d) without affecting the fulfilment of other conditions.

If all the equations (22a, b, c) are to be satisfied at the same time, there are definite requirements imposed on the focal length of the enlarging lens, or the magnification, requirements that have been described in the test.

One point of importance to note is implied in Equations 14 and 15, namely that in taking all distances are measured along the lens axis, which meets the plate or film in a point P , and that in enlarging all distances are measured along the line joining the point of projection and P . Normally this will coincide with the axis of the enlarging lens, and this in fact has been assumed throughout, except when dealing with the *Charles* method or the tilting lens. While introducing theoretical limitations it does not in fact introduce restrictions of great practical importance.

The most interesting results are obtained by fulfilling (22a and b) and making a compromise for the best definition overall. This is the basis of methods described on pp. 317-328. In particular it is evident from these equations that the tilting lens method and that due to *Charles* are essentially the same in principle : a value of $D(1)$ is chosen so that (22a, b) are satisfied and then an adjustment made to get a reasonably good definition overall.

EPILOGUE

There are some desirable features of the performance of a lens which cannot be realised because of the very nature of the light the lens is handling. For instance, because light travels in straight lines, it is impossible to have at the same time both a large aperture and a large depth of focus.

There are others, however, which are not attained because of the complication of lens construction that they would entail. For instance it is possible to make a lens of aperture $f0.8$ provided that only a small field is to be covered, say 16 mm. film with a lens of 2 inch–3 inch, or even longer focal length. There seems no fundamental reason why a lens of the same aperture should not be made to cover a larger field, but with present methods of lens construction and design this would probably mean an intolerable degree of complication.

In every lens produced a compromise has to be made. For instance in a telephoto lens some of the correction for zonal spherical aberration has normally to be sacrificed to obtain a reasonable distortion and astigmatism correction. There is no point in disguising the fact that every lens is a compromise. It has already been stressed that advertising and patent specification claims that aberrations have been eliminated are only a conventional way of saying that a reasonable compromise has been reached.

The fact that the aberrations are reduced to such an extent that the average photographer will not see them unless he looks carefully for them does not mean that they should be overlooked or their existence denied. It is only by recognising their presence and their effect on the definition of the negative that it is possible to exercise a proper judgment and discrimination when examining lenses, and to understand why only a limited number of basic styles of lens are available, for instance to understand why there is not available an $f1.5$ covering an angle of 100° .

It seems at the present that to make any substantial

movement in the way of producing lenses with a higher performance than those now available will mean the introduction of new materials and new manufacturing methods.

A great advance was made nearly half a century ago with the development at Jena of special glasses, glasses that are now regarded as being the common-place materials available to the designer and manufacturer. New glasses have been the subject of recent patents by Kodak. It seems that these will lead to definite improvement in lens performance.

Up to the present practically all photographic lenses commercially available have spherical polished surfaces on the glasses. If it were possible to produce non-spherical surfaces sufficiently accurately and cheaply to incorporate in normal commercial lenses an improvement in lens performance could be obtained. Non-spherical surfaces leave the designer with much greater freedom in arranging the various glasses. The difficulty is to produce them to close enough limits for use in photographic lenses. The glass surfaces are normally true to the proper curvature within one fifty-thousandth of an inch. This can readily be obtained with spherical surfaces. Before non-spherical surfaces can be produced in quantity to this accuracy new methods will have to be introduced.

It is too early yet to say whether moulded plastic lenses will find their way into high-grade camera lenses. In addition to the accuracy of the surface curvature mentioned above and which has to be dealt with in the form of allowing for shrinkage as the lenses come off the dies, there is also the question of complete uniformity of the transparent material to be dealt with. In the manufacture of high-grade optical glass stringent precautions are taken to ensure the uniformity of the glass, and at one time the methods of obtaining this uniformity were carefully guarded trade secrets. Considerable difficulties have yet to be overcome before a moulded lens can be produced with the same quality of uniform material and accurate finish that is characteristic of a first class anastigmat.

A development that seems to be foreshadowed by recent

patents and publications in technical literature, is a lens comprising one or more concave or convex mirrors and correcting plates of a non-spherical form, or more probably a system employing mirrors corrected for spherical aberration by deep meniscus lenses. These lenses are simple, light and comparatively free from chromatic effects. While the best theoretical correction is obtained with aspheric plates, these are difficult to manufacture and meniscus correcting elements, where manufacture is comparatively straightforward, will give adequate performance.

At present lenses of $f1.3$ aperture are available for the use of the film studios. It is doubtful whether any higher aperture will be needed for film or television studio use. Improvements in the television pick-up tubes mean that lenses of existing types provide ample light.

The variable focus or Zoomar lens is finding increasing use at present in the television studios. The studios are cramped for space and usually work to a tight schedule, so the variable focus lens provides an important method of securing close-ups and the effects of a gradual camera movement.

The first development of lenses, in what can be called the classic period, ending about 1905, was mainly stimulated by the demands of still photography. An aperture of $f3.5$ or $f3$ was considered quite fast for that work. The second period of lens development, starting about 1920, owed its inception to the demands of the film studios to a large extent, and to the development of the miniature camera to a lesser extent. It can be taken as culminating in lenses of apertures up to $f1.0$ and $f1.3$. Apertures are not likely to be increased much beyond this except for television projection lenses and for special purposes such as radiography, where maximum apertures have reached $f0.65$. Nor is it likely that radically new types will be brought out for commercial use. What can be expected is a gradual improvement in present types of lenses, in particular as far as vignetting is concerned, as new materials and techniques become available.

XXXII.—CONVERSION OF INCHES TO MILLIMETRES

| | | | | | | | | | | | | | | | | |
|--------|-----|-----|---------|----------|---------|---------|---------|---------|---------|---------|----------|---------|---------|---------|---------|---------|
| mm. | ... | ... | 7½ | 10 | 12½ | 15 | 17½ | 20 | 22½ | 25 | 26 | 27 | 28 | 29 | 30 | 32½ |
| Inches | ... | ... | 19/64 | 25/64 | ¼ | 19/32 | 11/16 | 25/32 | ⅜ | 63/64 | 33/32 | 1 1/16 | 1 3/32 | 1 9/64 | 1 11/64 | 1 9/32 |
| mm. | ... | ... | 35 | 37½ | 40 | 42½ | 45 | 47½ | 50 | 52½ | 55 | 57½ | 60 | 62½ | 65 | 67½ |
| Inches | ... | ... | 1⅛ | 1 15/32 | 9/16 | 1 43/64 | 1 49/64 | 1⅞ | 1 31/32 | 2 1/16 | 2 5/32 | 2 17/64 | 2 23/64 | 2 29/64 | 2 9/16 | 2 21/32 |
| mm. | ... | ... | 70 | 72½ | 75 | 77½ | 80 | 82½ | 85 | 87½ | 90 | 92½ | 95 | 97½ | 100 | 105 |
| Inches | ... | ... | 2⅞ | 2 27/32 | 2 61/64 | 3 3/64 | 3 5/32 | 3⅞ | 3 11/32 | 3 7/16 | 3 35/64 | 3 41/64 | 3⅞ | 3 27/32 | 3 15/16 | 4⅛ |
| mm. | ... | ... | 110 | 115 | 120 | 125 | 130 | 135 | 140 | 145 | 150 | 155 | 160 | 165 | 170 | 175 |
| Inches | ... | ... | 4 21/64 | 4 17/32 | 4 23/64 | 4 59/64 | 5 7/64 | 5 5/16 | 5⅞ | 5 45/64 | 5 29/32 | 6 3/32 | 6 19/64 | 6⅞ | 6 11/16 | 6 57/64 |
| mm. | ... | ... | 180 | 185 | 190 | 195 | 200 | 210 | 220 | 230 | 240 | 250 | 260 | 270 | 280 | 290 |
| Inches | ... | ... | 7 5/64 | 7 9/32 | 7 15/32 | 7 43/64 | 7⅞ | 8 17/64 | 8 21/32 | 9 3/64 | 9 7/16 | 9 27/32 | 10⅞ | 10⅞ | 11 | 11⅛ |
| mm. | ... | ... | 300 | 310 | 320 | 330 | 340 | 350 | 360 | 370 | 380 | 390 | 400 | 410 | 420 | 430 |
| Inches | ... | ... | 11⅞ | 12 3/16 | 12 9/16 | 13 | 13⅞ | 13⅞ | 14 3/16 | 14 9/16 | 14 15/16 | 15⅞ | 15⅞ | 16⅞ | 16⅞ | 16⅞ |
| mm. | ... | ... | 440 | 450 | 460 | 470 | 480 | 490 | 500 | 550 | 600 | 650 | 700 | 800 | 900 | 1000 |
| Inches | ... | ... | 17 5/16 | 17 11/16 | 18⅞ | 18⅞ | 18⅞ | 19⅞ | 19⅞ | 21⅞ | 23⅞ | 25 9/16 | 27⅞ | 31⅞ | 35⅞ | 39⅞ |

10 mm. = 1 cm., e.g. 145 mm. = 14.5 cm. 10.5 cm. = 105 mm.

1000 mm. = 100 cm. = 1 metre = 39.37". 1" = 25.4 mm.

XXXIII.—CONVERSION OF FEET TO METRES

| | | | | | | | | | | | | | | | |
|------------|-----|-----|-----|------|------|------|------|------|------|------|------|------|------|------|------|
| Feet ... | 2 | 2½ | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| Metres ... | .61 | .76 | .91 | 1.22 | 1.52 | 1.83 | 2.13 | 2.44 | 2.74 | 3.04 | 3.35 | 3.65 | 3.96 | 4.26 | 4.57 |

| | | | | | | | | | | | | | | | |
|------------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| Feet ... | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 |
| Metres ... | 4.87 | 5.18 | 5.48 | 5.79 | 6.09 | 6.39 | 6.70 | 7.01 | 7.31 | 7.61 | 7.92 | 8.22 | 8.52 | 8.83 | 9.13 |

| | | | | | | | | | | | | | | | |
|------------|------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Feet ... | 32 | 34 | 36 | 38 | 40 | 42 | 44 | 46 | 48 | 50 | 55 | 60 | 65 | 70 | 75 |
| Metres ... | 9.75 | 10.35 | 10.96 | 11.56 | 12.16 | 12.78 | 13.38 | 14.00 | 14.60 | 15.22 | 16.73 | 18.26 | 19.77 | 21.30 | 22.83 |

| | | | | | | | | | | | | | | | |
|------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Feet ... | 80 | 85 | 90 | 95 | 100 | 110 | 120 | 130 | 140 | 150 | 160 | 170 | 180 | 190 | 200 |
| Metres ... | 24.35 | 25.88 | 27.40 | 28.90 | 30.43 | 33.48 | 36.52 | 39.56 | 42.60 | 45.64 | 48.70 | 51.72 | 54.76 | 57.80 | 60.84 |

XXXIV.—CONVERSION OF DIOPTERS TO INCHES AND CENTIMETRES

| | | | | | | | | | | | |
|----------------------|------|-----|-------|-----|-------|----------|------|-------|-------|---------|-------|
| Power In Diopters... | 1 | 1½ | 2 | 2½ | 3 | 3½ | 4 | 4½ | 5 | 5½ | 6 |
| Focus In Centimetres | 400 | 200 | 133.3 | 100 | 66.67 | 50.0 | 40.0 | 33.33 | 28.58 | 25.0 | 22.22 |
| Focus In Inches | 157½ | 78½ | 52½ | 39½ | 26½ | 19 11/16 | 15½ | 13½ | 11½ | 9 27/32 | 8½ |

| | | | | | | | | | | | | | | |
|----------------------|--------|-------|-------|---------|-------|-------|--------|---------|------|--------|--------|--------|--------|--------|
| Power In Diopters... | 6½ | 7 | 7½ | 8 | 8½ | 9 | 9½ | 10 | 10½ | 11 | 11½ | 12 | 12½ | 13 |
| Focus In Centimetres | 15.38 | 14.29 | 13.34 | 12.50 | 11.75 | 11.11 | 10.53 | 10.0 | 9.53 | 9.09 | 8.70 | 8.33 | 8.00 | 7.69 |
| Focus In Inches | 6 1/16 | 5½ | 5½ | 4 59/64 | 4½ | 4½ | 4 5/32 | 3 15/16 | 3½ | 3 9/16 | 3 7/16 | 3 9/32 | 3 5/32 | 3 1/64 |

| | | | | | | | | | | | | | | |
|----------------------|---------|---------|---------|------|---------|---------|---------|--------|------|--------|------|--------|--------|---------|
| Power In Diopters... | 13½ | 14 | 14½ | 15 | 15½ | 16 | 16½ | 17 | 17½ | 18 | 18½ | 19 | 19½ | 20 |
| Focus In Centimetres | 7.41 | 7.14 | 6.89 | 6.67 | 6.45 | 6.25 | 6.06 | 5.88 | 5.72 | 5.56 | 5.41 | 5.27 | 5.13 | 5.00 |
| Focus In Inches | 2 15/16 | 2 13/16 | 2 23/32 | 2½ | 2 35/64 | 2 15/32 | 2 25/64 | 2 5/16 | 2½ | 2 3/16 | 2½ | 2 1/16 | 2 1/64 | 1 31/32 |

GLOSSARY

- ABERRATION.** A fault in the performance of a lens because of which the rays of light are not brought to a perfect point. The various types of aberration are dealt with in the text (see p. 94).
- ACHROMAT.** A lens designed to bring light of two colours to the same focus. Such a lens is *achromatised*, or is an *achromatic lens* (see p. 124).
- ALBADA FINDER.** A view-finder showing the area recorded marked by a white frame, set in a larger field than that recorded (see p. 297).
- ANASTIGMAT.** A lens constructed of a number of separated glass elements to give good definition over an appreciable size of plate or film (see p. 114).
- ANGLE OF VIEW.** The greatest angle between two rays going through the lens to the sensitive plate or film (see p. 44).
- ANGULAR FIELD.** The same as *Angle of View*.
- APOCHROMAT.** A lens in which light of three colours is brought to the same focus. Frequently used in process work (see p. 126).
- ASTIGMATISM.** A lens suffers from *astigmatism* when the rays from a point in front of the lens meet in two bars of light at right angles with a separation between them (see p. 113).
- AXIS.** The centres of the spherical surfaces bounding the glasses in a lens lie on a straight line, the *axis* of the lens. The lens is symmetrical about its axis (see p. 14).
- BACK FOCUS.** The distance from the back glass of a lens to the focusing screen when a distant object is in sharp focus on the latter (see p. 29).
- BARREL DISTORTION.** A lens suffers from *barrel distortion* when the images of straight lines are curved lines concave to the centre of the plate or film (see p. 121).
- CENTRE OF FIELD.** The point where the *lens axis* cuts the sensitive plate or film (see p. 103).
- CENTRAL DEFINITION.** The quality of the definition in the centre of the field. It depends only on the *spherical aberration* and *chromatic aberration* (see p. 103).
- CHROMATIC ABERRATIONS.** Faults in the performance of a lens that arise because light of different colours is bent to varying extents by the same piece of glass. Subdivided into *axial* and *lateral chromatic aberrations* (see p. 100).
- COMA.** A fault in lens performance that results in an unsymmetrical light patch, flaring away like the tail of a comet (see p. 110).
- COMPOUND LENS.** A lens consisting of two or more pieces of glass, sometimes cemented together with Canada Balsam (see p. 14).
- CONDENSER.** A lens or lens system concerned mainly with the even distribution of light and not with the quality of an image (see p. 314).
- CONVERTIBLE LENS.** A lens whose component parts may be used alone to provide lenses of different focal lengths (see p. 186).
- CONVERGENCE OF PERPENDICULARS.** When a photograph is taken with the camera pointing slightly upwards the parallel edges of buildings are reproduced as sloping together (see p. 317).
- CORRECTION OF DISTORTION.** The *convergence of perpendiculars* can be remedied when an enlargement is made by using a sloping enlarging board, with or without a sloping negative, when suitable precautions are taken (see p. 317).

COVERING POWER. The area of plate or film over which the lens will give an image of reasonable quality, or the region of space that is recorded on a plate or film of this size (see p. 44).

CONVERGING LENS. A lens which causes previously diverging rays of light to converge together, or which increases the degree of convergence of already converging rays (see p. 27).

DEFINITION. The quality of the image produced by a lens (see p. 12).

DEPTH OF FIELD. The region in front of and behind the focused distance, within which object points still produce an image of a required standard of sharpness. It is the tolerance in object lens distances (p. 59).

DEPTH OF FOCUS. The permissible film movement, or tolerance in lens-film distances, within which the sharpness of the image from a fixed object is up to a required standard (p. 68).

DIFFRACTION. Light has a certain tendency to spread into the shadow of an object, or to spread away from a point image. This is the *diffraction* of light. In general it is not appreciable (see p. 137).

DISPERSION. The *dispersion* of glass is its property of bending light of different colours to different extents. It is measured by the *Abbe number V* (see p. 96).

DISTORTION. A lens suffering from distortion reproduces straight lines in the object space as curved lines on the sensitive plate or film. See *Barrel Distortion* and *Pincushion Distortion* (see p. 119).

DIVERGING LENS. A lens which increases the divergence of a group of already diverging light rays (see p. 27).

ENLARGING LENS. A lens designed to give its best performance under the conditions met with in making enlargements (see p. 135).

EQUIVALENT FOCUS. The same as *Focal Length*.

FIELD. The region of space that is not on the lens axis. Any point away from the lens axis is *in the field*. Correspondingly the image of a point in the field lies away from the centre of the sensitive plate or film (see p. 119).

FIELD CURVATURE. When there is *field curvature* the images of points in the field at a given distance from the lens, instead of being imaged on a plane surface, are imaged on a curved surface and the plate or film needs to be bent to fit this surface to get the best definition. The *field curvature* depends on the *Petzval sum* (see p. 113).

FLARE. The distribution of extraneous light on the plate or film due to light that has been reflected at two air-glass surfaces in the lens, when this light produces a more or less even illumination (see p. 258).

f/NUMBER. A number measuring the light passing power of a lens, and obtained by dividing the focal length by the diameter of the beam of light that gets through the lens. The smaller the *f/number* the more light is passed by the lens. Halving the *f/number* increases the light four-fold (see p. 62).

FOCAL LENGTH. The distance from a *nodal point* to a *focal point* of a lens. It settles the scale of reproduction (see p. 14).

FOCAL PLANE. A plane at right angles to the lens axis through the *focal point*. Infinitely distant objects image in this plane (see p. 24).

FOCAL POINT. The position of the *focus* when the rays entering or leaving the lens are a parallel bundle to the lens axis. The *focus* corresponding to an infinitely distant point on the lens axis (see p. 14).

- FOCUS** The point where the rays of light radiating from a luminous point and bent by a lens meet again, or the position where they come to their most compact form as judged by the size of the illuminated area they produce on a screen or sensitive plate placed there. Ideally this light patch is a point (see p. 12).
- FOCUSING.** The adjustment of a lens relative to a screen or sensitive plate so that the focus of any given point or group of points lies on it (see p. 16).
- FOCUSING SCREEN.** A ground glass screen placed in the camera in the position of the sensitive plate or film so that by inspection of the image formed upon this the *focusing* of the lens can be carried out. When the image is at its best on the ground glass screen then it is so also on the sensitive plate or film. The image is formed on the ground surface of the glass closest to the lens (see p. 291).
- FOCUSING SCALE.** A scale mounted on the camera so that the focusing of the lens can be carried out without a screen (see p. 235).
- GHOST IMAGE.** An image formed by rays which have been reflected at two air-glass surfaces inside the lens, and which lies near the image formed by rays going through the lens in the normal way (see p. 258).
- IMAGE POINT.** The same as *Focus*.
- INVERTED TELEPHOTO.** A lens consisting of a diverging group of lenses followed by a converging group so that the back focus of the system is greater than the focal length of lens as a whole (see p. 205).
- LENS.** A term used elastically to mean either a single piece of glass with polished faces, or a number of such pieces of glass mounted together, so that they are capable of bending light rays (see p. 12).
- LENS CENTRING.** The adjustment of a lens so that the centres of all the polished spherical surfaces of the glasses lie on a straight line (see p. 204).
- MENISCUS LENS.** A lens having one of its glass to air surfaces convex and the other concave (see p. 141).
- NODAL POINTS.** Two points on the lens axis such that a ray of light going into the lens aiming at one comes out of the lens aiming away from the other and parallel to its ingoing direction (see p. 26).
- PARALLAX ERROR.** The error introduced because the view-finder on a camera sees the scene from a different viewpoint to that of the camera lens, and so the area seen in the view-finder is not that recorded on the sensitive plate or film (see p. 298).
- PERFECT LENS.** A lens which reproduces every point as a point, and every straight line as a straight line (see p. 23).
- PERSPECTIVE.** The perspective of a group of objects is their relative grouping and sizes as it appears to the eye viewing them (see p. 33).
- PETZVAL LENS.** A lens consisting of two widely separated groups of lenses, each group approximately achromatic. Such a lens is very popular for projection work (see p. 144).
- PETZVAL SUM.** A quantity depending only on the glasses and the curves on them that are used in the lens, and which determines the *curvature of field*. The greater the Petzval sum the more curved is the field (see p. 113).
- PINCUSHION DISTORTION.** A lens suffers from pincushion distortion when the images of straight lines are curved lines convex towards the centre of the plate (see p. 121).

- POLARISED LIGHT.** With a *polarising filter* the light transmitted is *polarised* and has this property : if two polarising filters are *parallel* the light transmitted by the first is transmitted unchanged by the second ; if the second is turned through a right angle so that the filters are *crossed* the light that is transmitted by the first is completely extinguished by the second (see p. 272).
- POWER OF TELEPHOTO LENS.** This is the ratio of the focal length of a telephoto lens to the back focus of the lens (see p. 194).
- RAY.** The path along which light travels (see p. 11).
- RANGE-FINDER.** A device for estimating the distance of an object which is to be photographed (see p. 302).
- REFRACTIVE INDEX.** A number which measures the power of glass to bend light rays. The greater the refractive index the more a ray of light is bent (see p. 96).
- RESOLVING POWER.** The power of a lens to produce images of closely spaced lines or points which do not overlap one another, and which can be picked out as separate from one another (see p. 248).
- SPECTRUM.** The coloured patch of light, red at one end and shading off through orange, yellow, green, and blue to violet, produced when a beam of white light is bent by a prism before it falls on a screen (see p. 19).
- SPHERICAL ABERRATION.** The defect in the performance of a lens that results in its producing a disc of light as the image of a point on the lens axis, which has a certain minimum size that cannot be reduced by focusing the lens, but which can be reduced by stopping down the lens (see p. 103).
- STEREOSCOPIC EFFECT.** The two eyes see the same scene from slightly different viewpoints, and consequently two slightly different impressions of the scene are transmitted to the brain. The mental fusion of these two impressions to give a sensation of depth and relief is the *stereoscopic effect* (see p. 306).
- SURFACE TREATMENT.** The production of a thin film on the surface of glass of suitably adjusted refractive index and thickness so that no light is reflected at the surface. This eliminates *Ghost Images and Flare* (see p. 284).
- SUPPLEMENTARY LENS.** A lens, usually of a single piece of glass or of two cemented together, which when used with a camera lens may shorten the focal length so that close-ups may be taken or so that more of a distant scene may be recorded on a smaller scale; or may lengthen the focal length so that a distant scene may be reproduced on a larger scale (see p. 53).
- TELEPHOTO LENS.** A lens consisting of a converging group of lenses followed by a diverging group so that the back focus of the lens is only a fraction, about one-half or one-third, of the equivalent focal length of the lens (see p. 194).
- VIEW-FINDER.** A device mounted on the camera to indicate the part of a scene that will be recorded (see p. 291).
- VIGNETTING.** The lower intensity of illumination produced by a lens at the corner of the plate compared with the central illumination, due to the obstruction of light by the edges of the glasses (see p. 257).
- WIDE-ANGLE LENS.** A lens capable of giving satisfactory definition over a plate having a diagonal 1.5 to 2.5 times the focal length of the lens (see p. 172).

BIBLIOGRAPHY

Since the appearance of the first edition a number of enquiries have been received about books dealing with optical matters from a more technical point of view than is within the scope of this book. A number of works dealing with such topics are therefore listed below, with a few comments.

Probably the best technical book on photographic optics is

"Das photographische Objektiv," by *Marté, Richter, and v. Rohr* (Springer, Vienna, 1932).

An earlier book of the same type, of value despite its early date, is

"Theorie und Geschichte des photographischen Objektivs," by *v. Rohr* (Springer, Berlin, 1899). (An English edition, now out of print, was issued by *H.M. Stationery Office* in 1920).

Excellent accounts of aberration theory, using elementary mathematics, are given in

"Lehrbuch der Geometrischen Optik," by *A. Gleichen* (Teubner, Leipzig, 1902),

"Grundzüge der Theorie der optischen Instrumente," by *S. Czapski* (Barth, Leipzig, 1904),

"Principles and Methods of Geometrical Optics," by *J. P. C. Southall* (MacMillan, New York, 2nd Edition, 1913).

A more academic tone characterises

"The Theory of Optical Instruments," by *E. T. Whittaker* (Cambridge University Press)

More advanced mathematical methods are used to furnish an elegant treatment of aberration theory in

"The Symmetrical Optical System," by *G. C. Steward* (Cambridge University Press, London, 1928), and

"Geometrical Optics," by *J. L. Synge* (Cambridge University Press, London, 1937).

"Applied Optics and Optical Design," by *A. E. Conrady* (Oxford University Press) is Part One of a two volume work. Part Two has not appeared. This gives a good account of ray-tracing methods, but is of limited interest to the photographic lens designer. It is to be recommended as an introduction to the theory of optical design for those whose mathematics are weak.

As elementary treatments may be recommended

"Mirrors, Prisms and Lenses," by *J. P. C. Southall* (MacMillan, New York, 1918), and

"Geometrical Optics," by *H. T. Flint* (Methuen, London, 1936).

From the point of view of production methods, two recent books are outstanding,

"Optical Workshop Principles," by *Ch. Dévé* (Hilger, London, 1944), which is a translation from the French, and

"Prism and Lens Making," by *F. Twyman* (Hilger, London, 1942).

"Fundamentals of Optical Engineering," by *D. H. Jacobs* (McGraw-Hill, New York, 1943), contains a certain amount of aberration theory, and an account of methods of mounting optical elements.

This makes no pretence at being a comprehensive list. But there are enough types of book given to carry the interested reader a good way.

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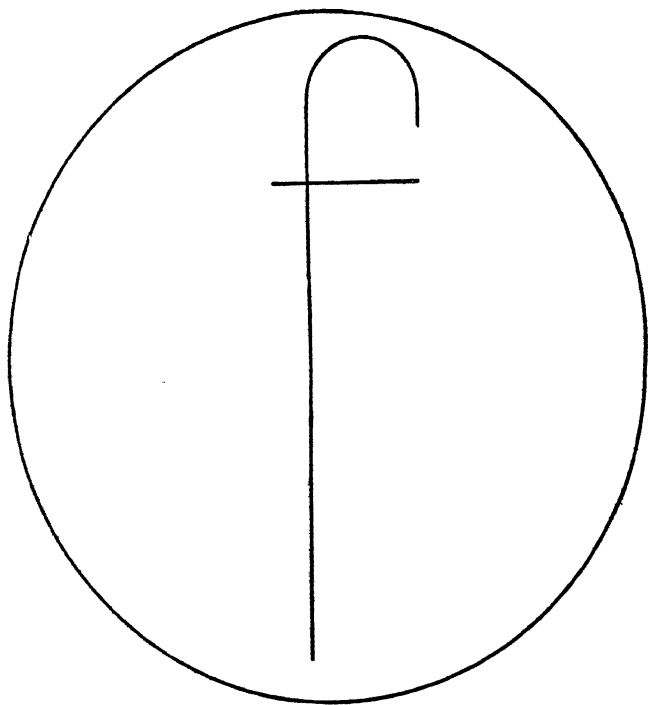
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